Nuclear PDFs: Status and Prospects

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Outline

I A brief overview of the existing nuclear PDFs

II The case of neutrino-nucleus DIS data

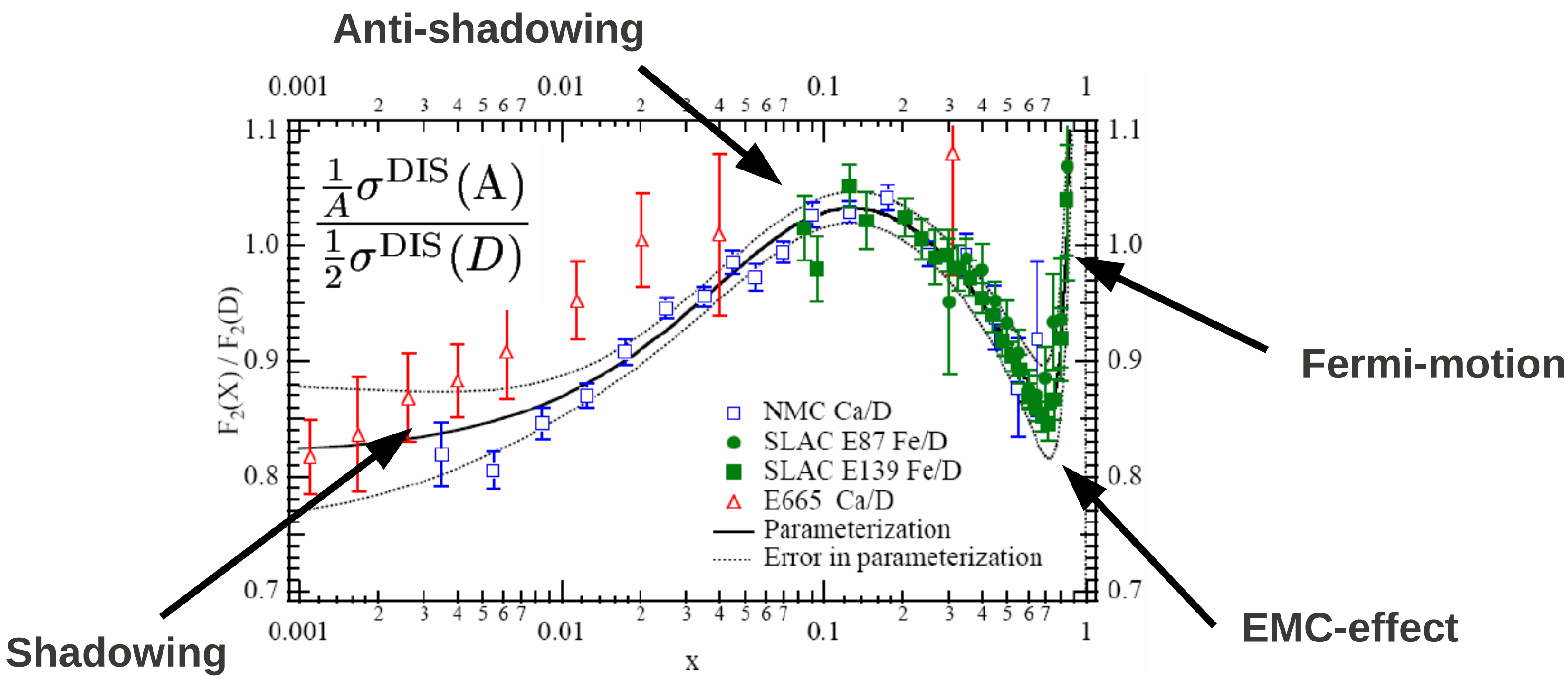
III Exciting dijet results from the LHC p+Pb run

IV LHeC & EIC prospects

V Summary

I A brief overview of the exisiting nuclear PDFs

Global nPDF fits – tests of factorization



- **General observation:** $\sigma^{\text{bound nucleon}} \neq \sigma^{\text{free nucleon}}$
- **Search for <u>process independent</u> nPDFs to realize such differences**

$$\sigma_{\rm DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\bar{q},g} f_i^A(\mu^2) \otimes \hat{\sigma}_{\rm DIS}^{\ell+i\to\ell+X}(\mu^2)$$

Nuclear PDFs, obeying the standard DGLAP

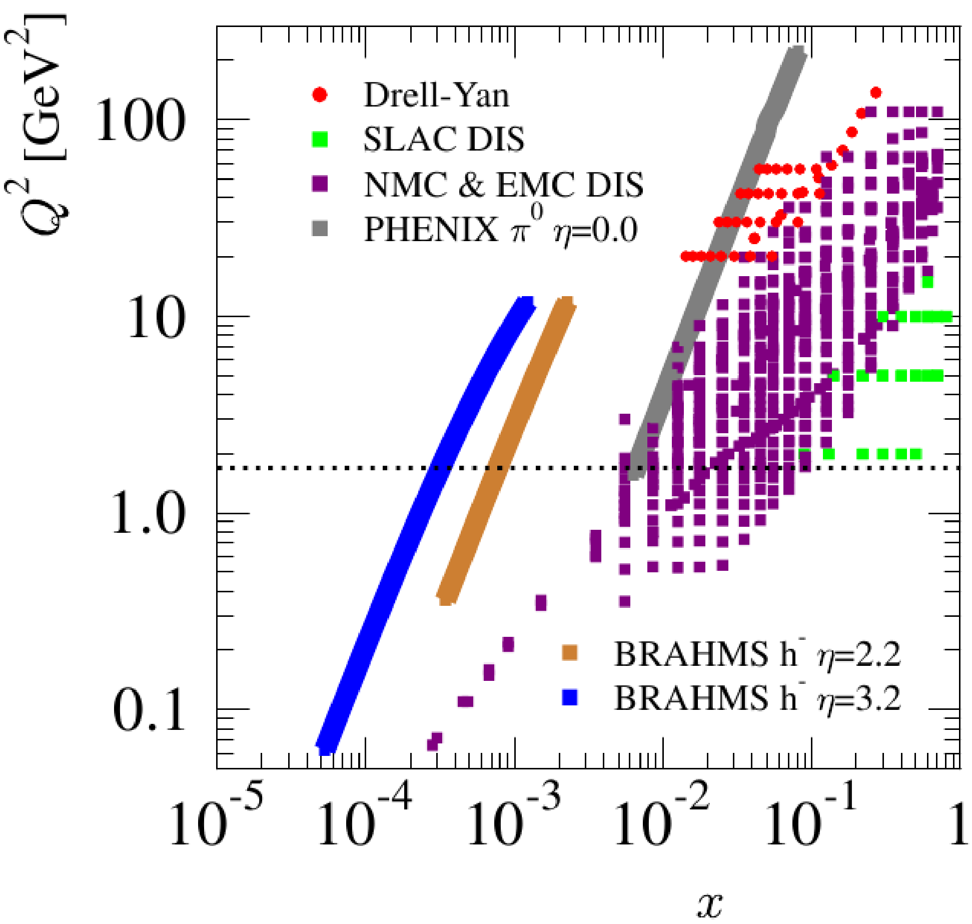
Usual perturbative coefficient functions

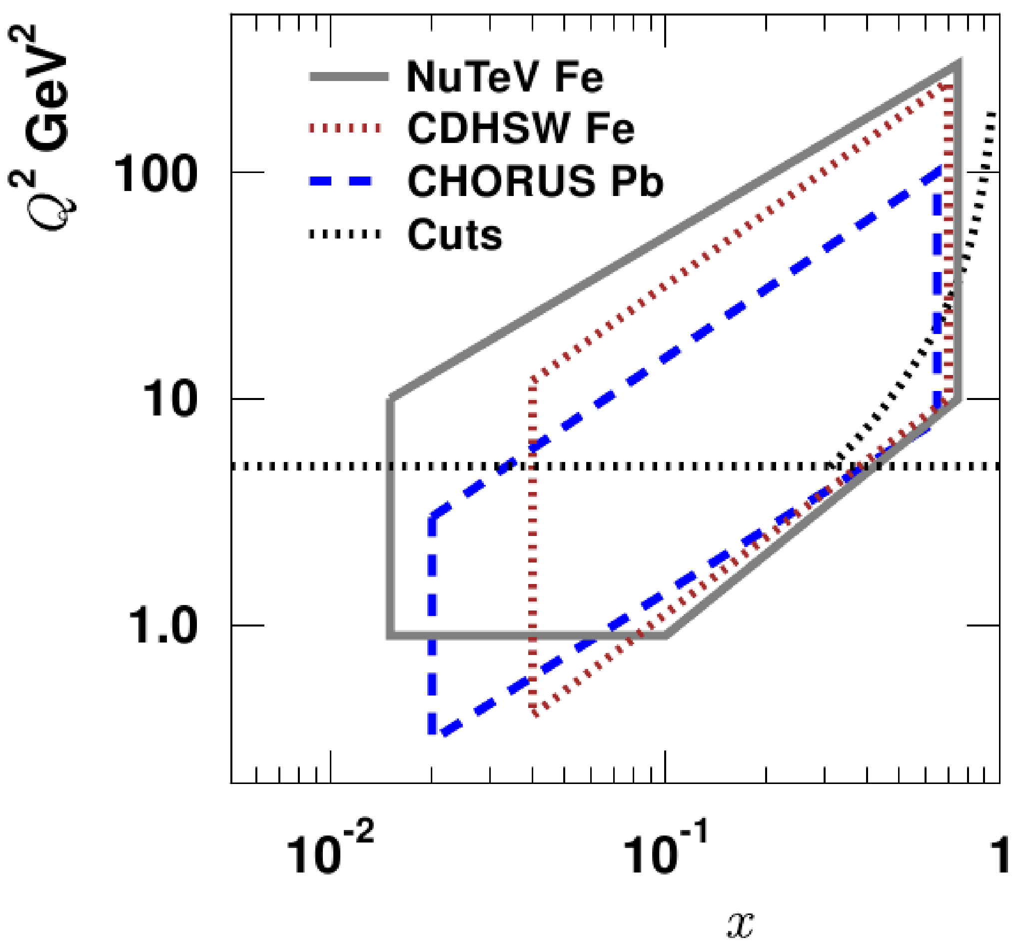
The contemporary NLO nPDF fits

$$f_i^{p,A}(x,Q^2) = R_i^A(x,Q^2) f_i^p(x,Q^2)$$

	HKN07	EPS09	DSSZ	nCTEQ prelim.
Ref.	Phys. Rev. C76 (2007) 065207	JHEP 0904 (2009) 065	Phys.Rev. D85 (2012) 074028	arXiv:1307.3454
Order	LO & NLO	LO & NLO	NLO	NLO
Neutral current e+A / e+d DIS	√	√	√	√
Drell-Yan dileptons in p+A / p+d	√	√	√	√
RHIC pions in d+Au / p+p		√	√	
Neutrino-nucleus DIS			√	
Q^2 cut in DIS	1GeV	1.3GeV	1GeV	2GeV
# of data points	1241	929	1579	708
Free parameters	12	15	25	17
Error sets available		√	√	√
Error tolerance $\Delta\chi^2$	13.7	50	30	35
Baseline	MRST98	CTEQ6.1	MSTW2008	CTEQ6M
Heavy quark treatment	ZM_VFNS	ZM_VFNS	GM_VFNS	GM_VFNS

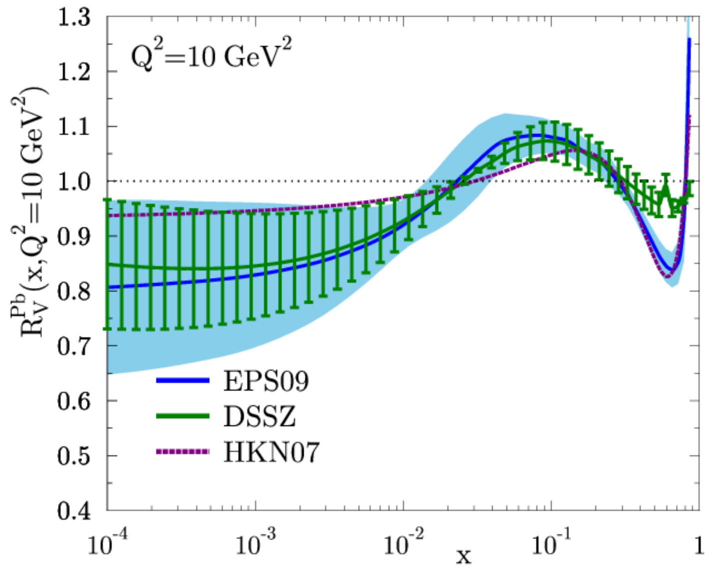
Kinematical coverage of the nuclear data





Comparison: Valence quarks

- Some differences between EPS09, HKN07 & DSSZ…. (data constraints for x=0.1…1)



(R_{uV} & R_{dV} almost the same for EPS09, DSSZ, HKN07)

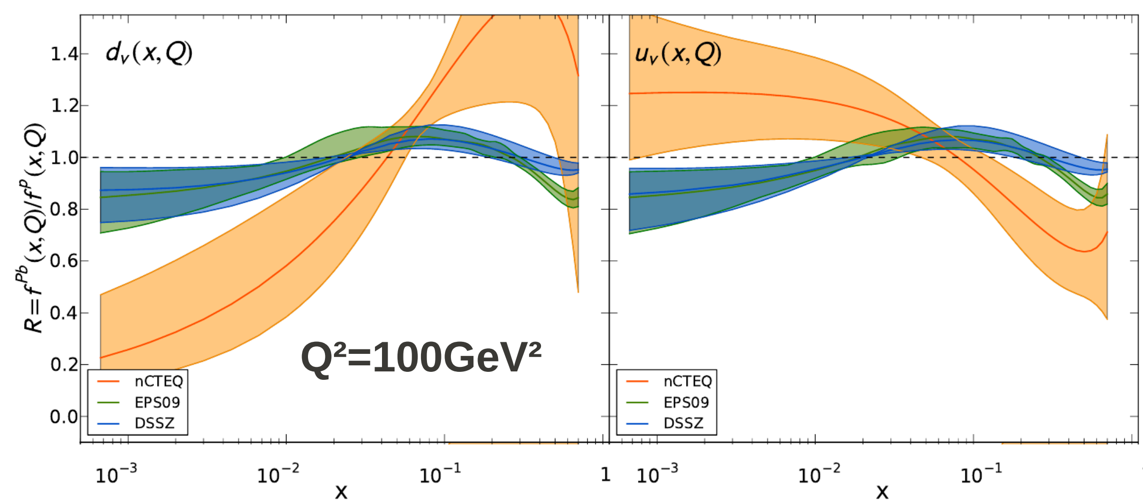
Clear diasgreement at large x. An isospin effect?

- …but the preliminary nCTEQ curves show a really drastic difference

$$d\sigma^{\rm DIS} \sim \left(\frac{4}{9}\right) u_v^A + \left(\frac{1}{9}\right) d_v^A$$

$$\sim u_v^A \left[R_{u_v} + R_{d_v} \frac{d_v^p}{u_v^p} \frac{Z+4N}{N+4Z} \right]$$

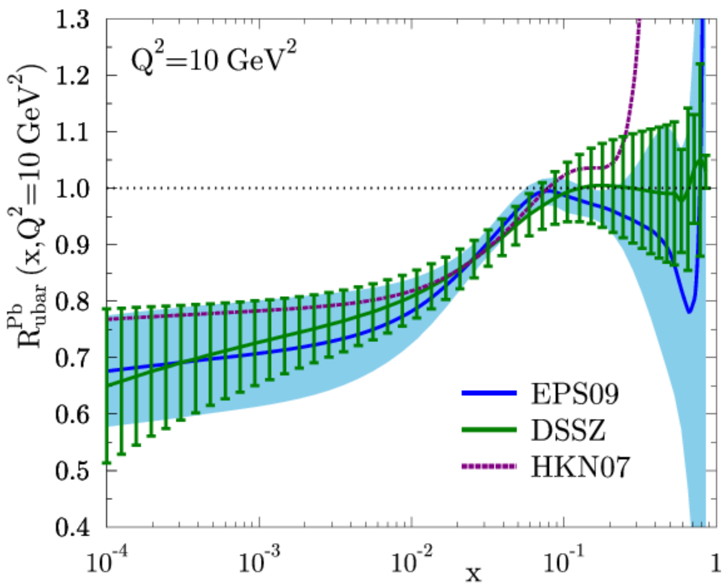
$$\approx u_v^A \left[R_{u_v} + \frac{1}{2} R_{d_v} \right]$$



- No real constraints for R_{uV} and R_{dV} separately!

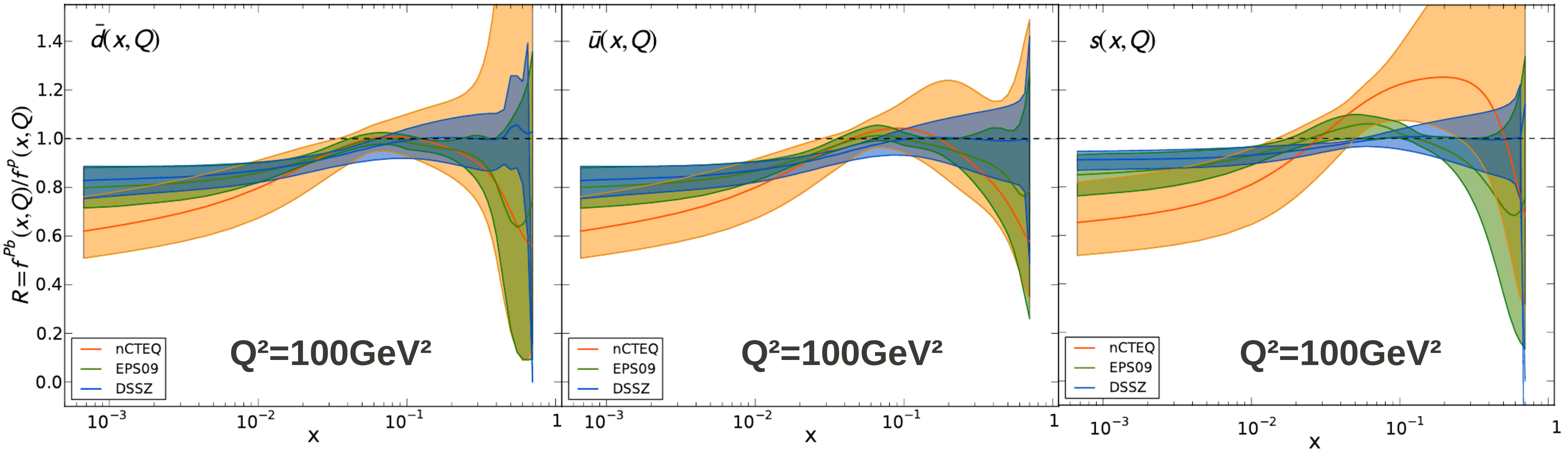
Comparison: Sea Quarks

- **No qualitative disagreements in the data constrained region (x=0.01...0.1)**



The large-x behaviour reflects the gluons (above the parametrization scale)

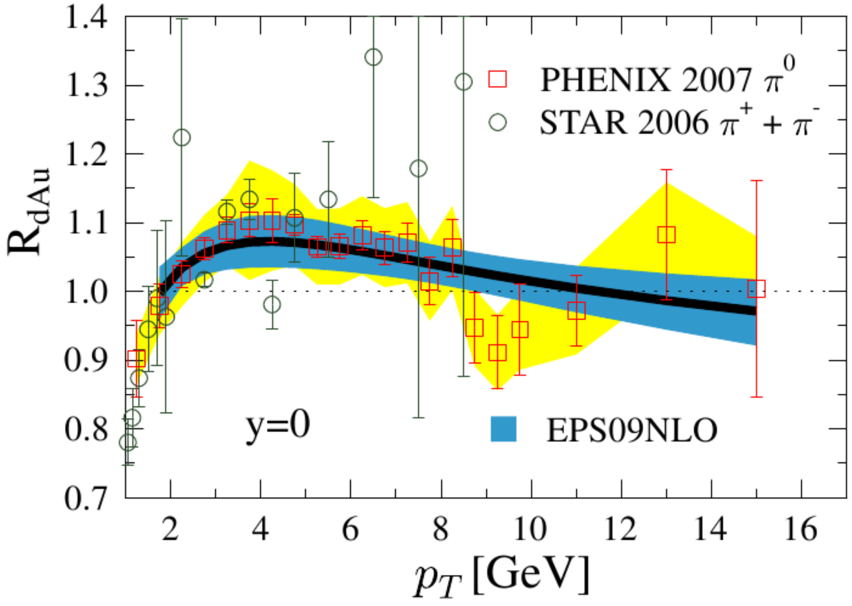
- **No qualitative disagreements to preliminary nCTEQ results either**

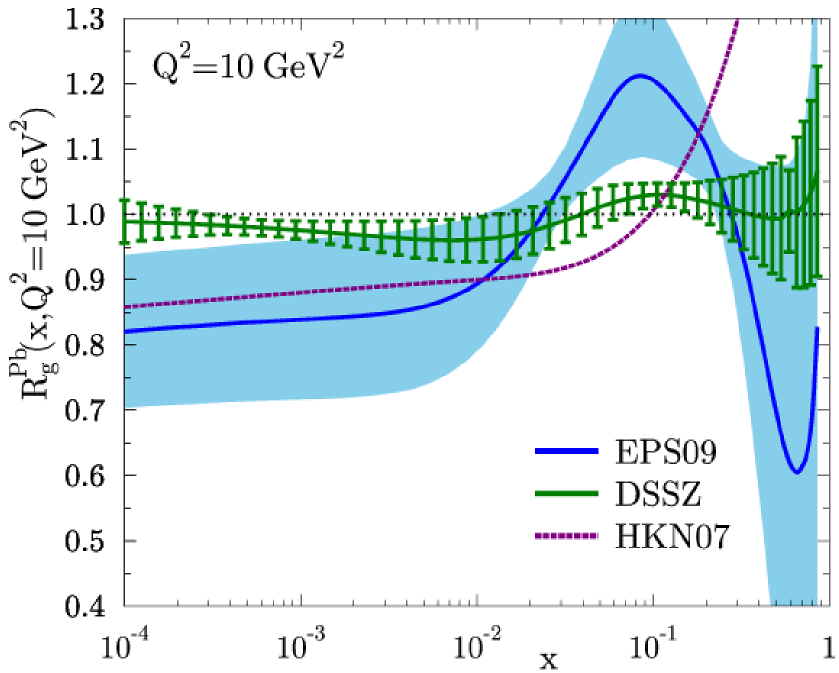


Comparison: Gluons

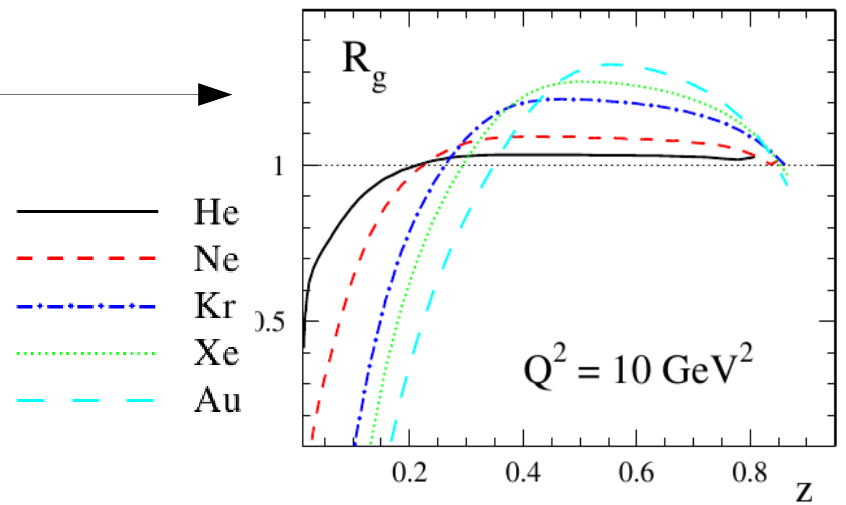
- **Difference between EPS09 & DSSZ:**

*The antishadowing and EMC effect in **EPS09** comes from the RHIC pion data*





FF(g→pion,A) / FF(g→pion,p)



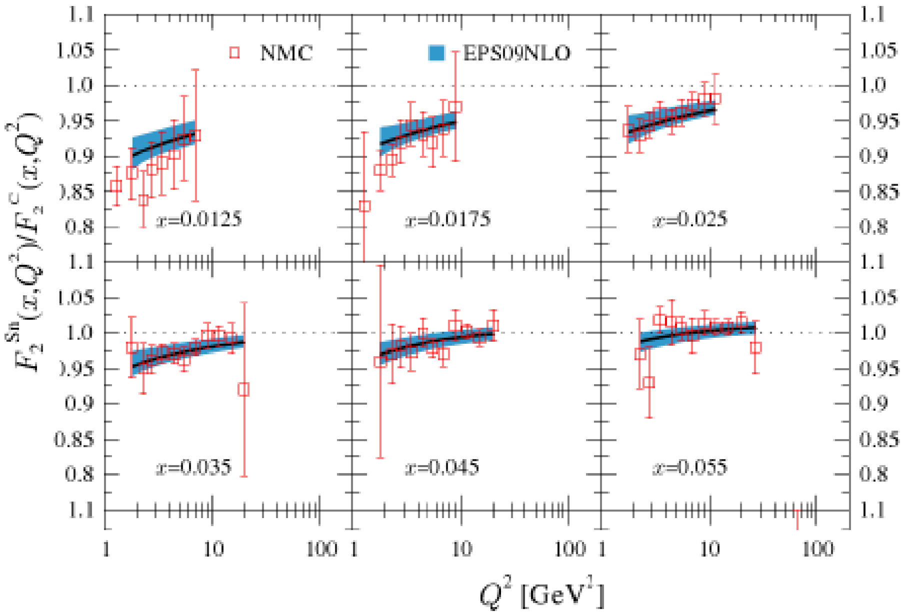
***DSSZ** advocated nuclear modifications in the fragmentation functions. No antishadowing nor EMC effect.*

Both can fit the pion data, but the origin of the effect is different physics.

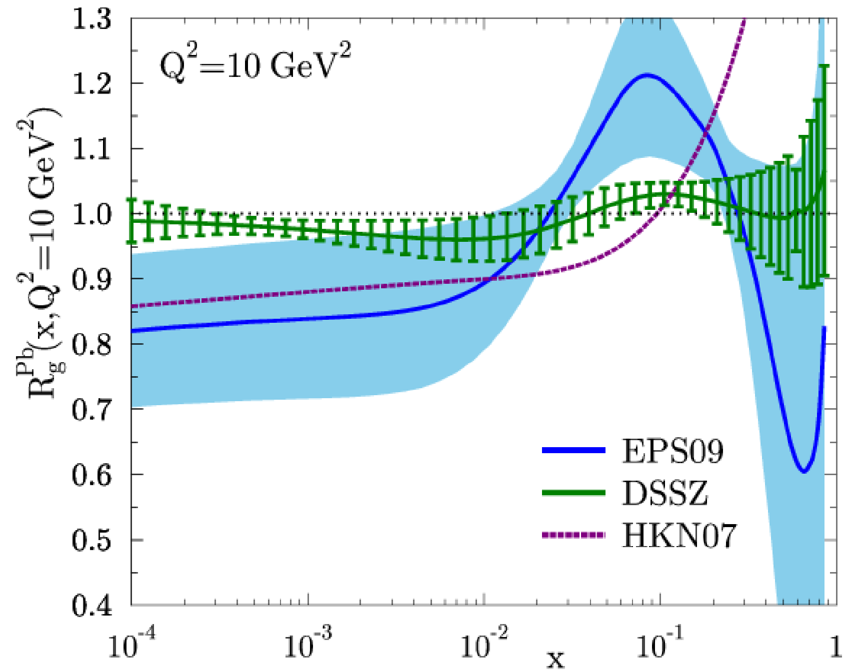
Comparison: Gluons

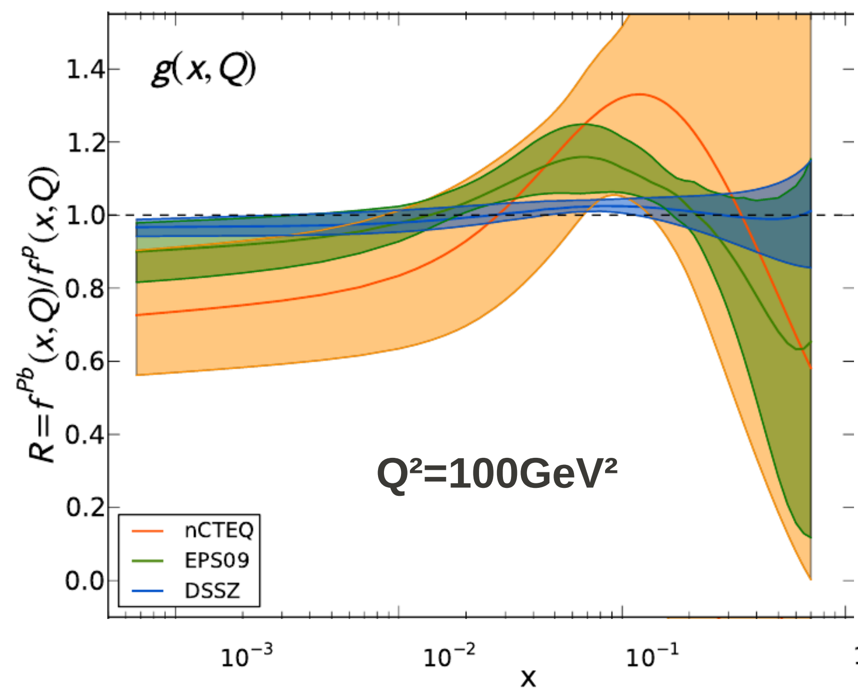
- ***Strongest shadowing and largest error band in nCTEQ***

Higher Q^2 cut has removed part of the small-Q^2 DIS data (largest DGLAP effects).



No pion data included yet





II The case of neutrino-nucleus DIS data

Some remarks regarding neutrino DIS

- **Neutrino DIS probes different partonic combinations than e.g. the charged lepton DIS**

→ **Complemtentary information on the PDFs (especially the strange quark)**

$$d^2\sigma^{\nu A} \propto \left(d^A + s^A + b^A\right) + (1-y)^2\left(\overline{u}^A + \overline{c}^A\right)$$
$$d^2\sigma^{\overline{\nu} A} \propto \left(\overline{d}^A + \overline{s}^A + \overline{b}^A\right) + (1-y)^2\left(u^A + c^A\right)$$

vs.

$$d^2\sigma^{\ell^\pm A} \propto \frac{4}{9}\left(u^A + c^A + \overline{u}^A + \overline{c}^A\right) + \frac{1}{9}\left(d^A + s^A + b^A + \overline{d}^A + \overline{s}^A + \overline{b}^A\right)$$

- **Data taken with heavy targets (Fe, Pb)** → **Nuclear PDFs**

- **The adequacy of the factorization in nuclear neutrino DIS has been studied by independent groups. The conclusions are contradictory:**

nCTEQ: **No** ; *Paukkunen & Salgado*: **Yes** ; *De Florian et.al (DSSZ)*: **Yes**

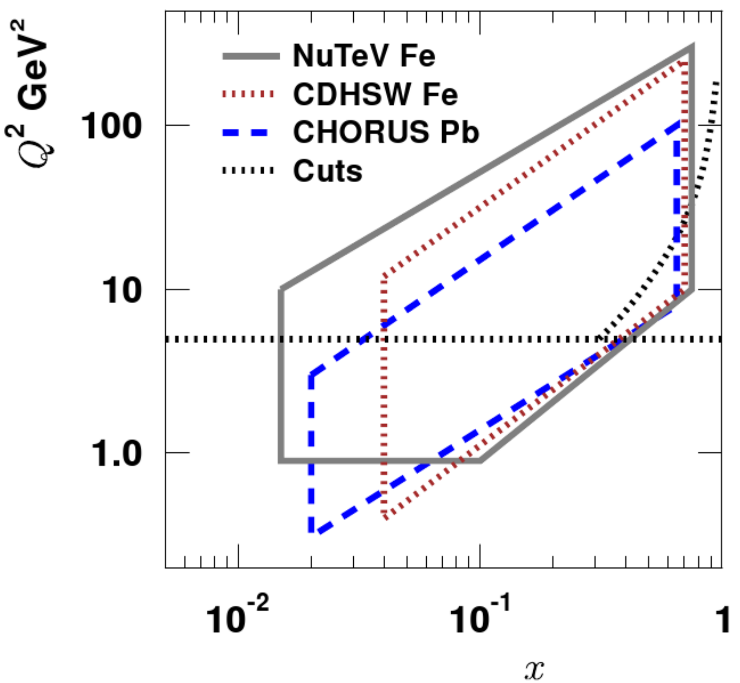
Phys. Rev. D77 054013 (2008)
Phys. Rev. D80 094004 (2009)
Phys. Rev. Lett. 106, 122301 (2011)

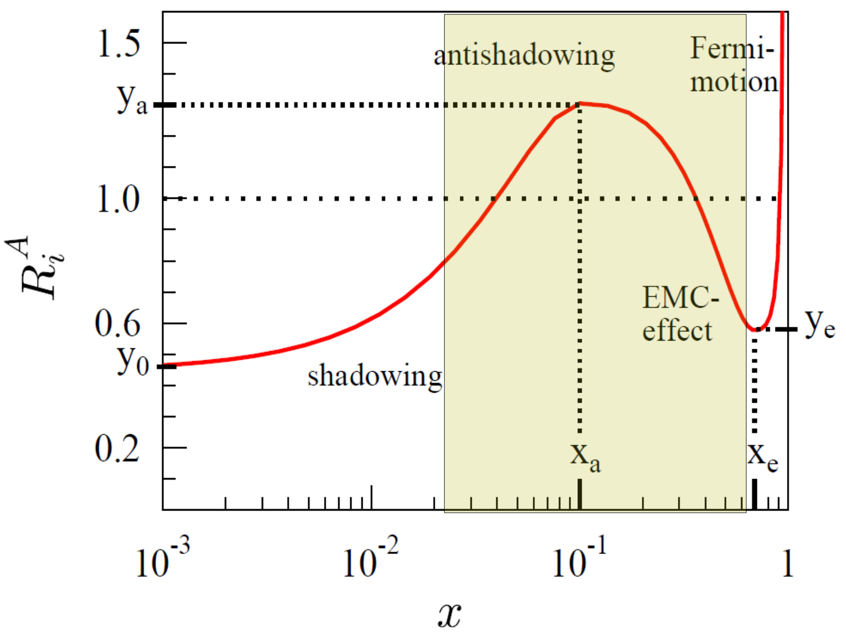
JHEP 1007 (2010) 032
Phys.Rev.Lett. 110 (2013) 212301

Phys.Rev. D85 (2012) 074028

The high-energy neutrino data

- **Three independent data sets:** **NuTeV (Fe), CDHSW (Fe) and CHORUS (Pb) (absolute cross sections)**





- **Typical kinematical cuts:** $Q^2_{\rm cut} > 4\,{\rm GeV}^2$, and $W^2_{\rm cut} > 12.25\,{\rm GeV}^2$

→ **~ 2000 NuTeV, 1000 CHORUS, 1000 CDHSW datapoints**

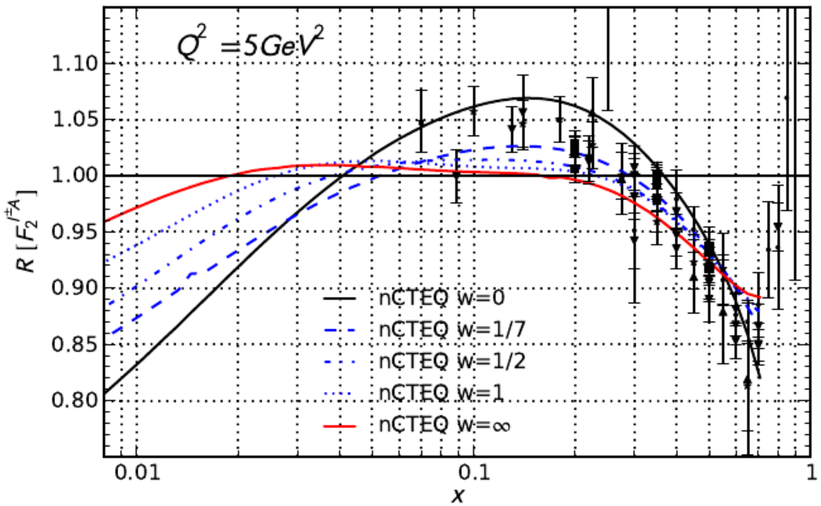
- **The large kinematical overlap should enable to check the mutual compatibility**

Neutrinos: The nCTEQ work

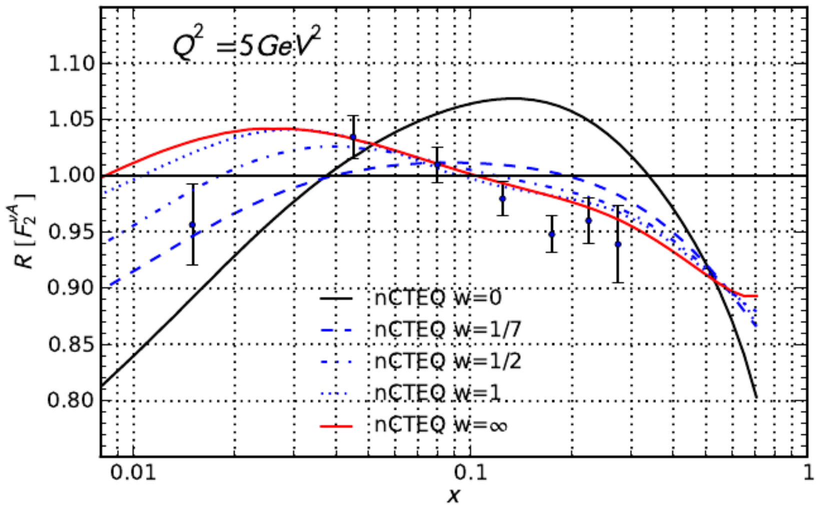
- **The nCTEQ claimed for having observed non-universal nuclear effects in the NuTeV cross-section data**

Phys. Rev. D77 054013 (2008)
Phys. Rev. D80 094004 (2009)

Some charged lepton data



Some NuTeV neutrino data data



Fit to the NuTeV neutrino data

Neutrinos: The nCTEQ work

- A global nPDF analysis including NuTeV & CHORUS neutrino cross-section data

$$\chi^2 = \sum_{l^\pm A \text{ data}} \chi_i^2 + \sum_{\nu A \text{ data}} w \chi_i^2$$

$l^\pm A$ gets worse as w is increased

Phys. Rev. Lett. 106, 122301 (2011)

TABLE II. Summary table of a family of compromise fits.

w	$l^\pm A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
0	708	638 (0.90)	···	···	638 (0.90)
1/7	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
1/2	708	680 (0.96)	3134	4405 (1.40)	5085 (1.32)
1	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
∞	···	···	3134	4192 (1.33)	4192 (1.33)

νA gets worse as w is decreased

- No satisfactory simultaneous fit to both $l^\pm A$ and νA data
- The use of NuTeV correlated errors was underscored. The same conclusion was, however, reached when adding all errors in quadrature.

Neutrinos: Paukkunen & Salgado

JHEP 1007 (2010) 032

- **An independent systematic comparison**

  - More diverse set of neutrino DIS data: **NuTeV (Fe), CDHSW (Fe) and CHORUS (Pb)**
  - The target mass corrections according to Accardi & Qiu *[JHEP 0807 (2008) 090]*

$$\int_x^1 \frac{dz}{z}\omega_{ik}(z)\, f_k^A\left(\frac{x}{z}\right) \rightarrow \int_x^1 \frac{dz}{z}\omega_{ik}(z)\, f_k^A\left(\frac{\xi}{z}\right) \qquad \xi \equiv 2x/(1+\sqrt{1+4x^2M^2/Q^2})$$

  - Electroweak radiation Bardin et.al *[JHEP 0506 (2005) 078]* as a part of the cross-sections

$$F_i^A = \sum_k \left[\omega_{ik}^{\mathrm{LO}}\left(1+\Delta_k^{\mathrm{radiative}}\right) + \omega_{ik}^{\mathrm{NLO}}\right] \otimes f_k^A$$

  - No PDF-fitting involved, just a systematic comparison employing CTEQ6.6 & EPS09

- **Present the data as a weighted average**

$$R_{\mathrm{Average}}^{\mathrm{CTEQ6.6}} \equiv \left(\sum_{i\in \mathrm{fixed}\, x}^{N} \frac{R_i^{\mathrm{CTEQ6.6}}}{\sigma_i}\right)\left(\sum_{i\in \mathrm{fixed}\, x}^{N} \frac{1}{\sigma_i}\right)^{-1} \pm N \times \left(\sum_{i\in \mathrm{fixed}\, x}^{N} \frac{1}{\sigma_i}\right)^{-1}$$

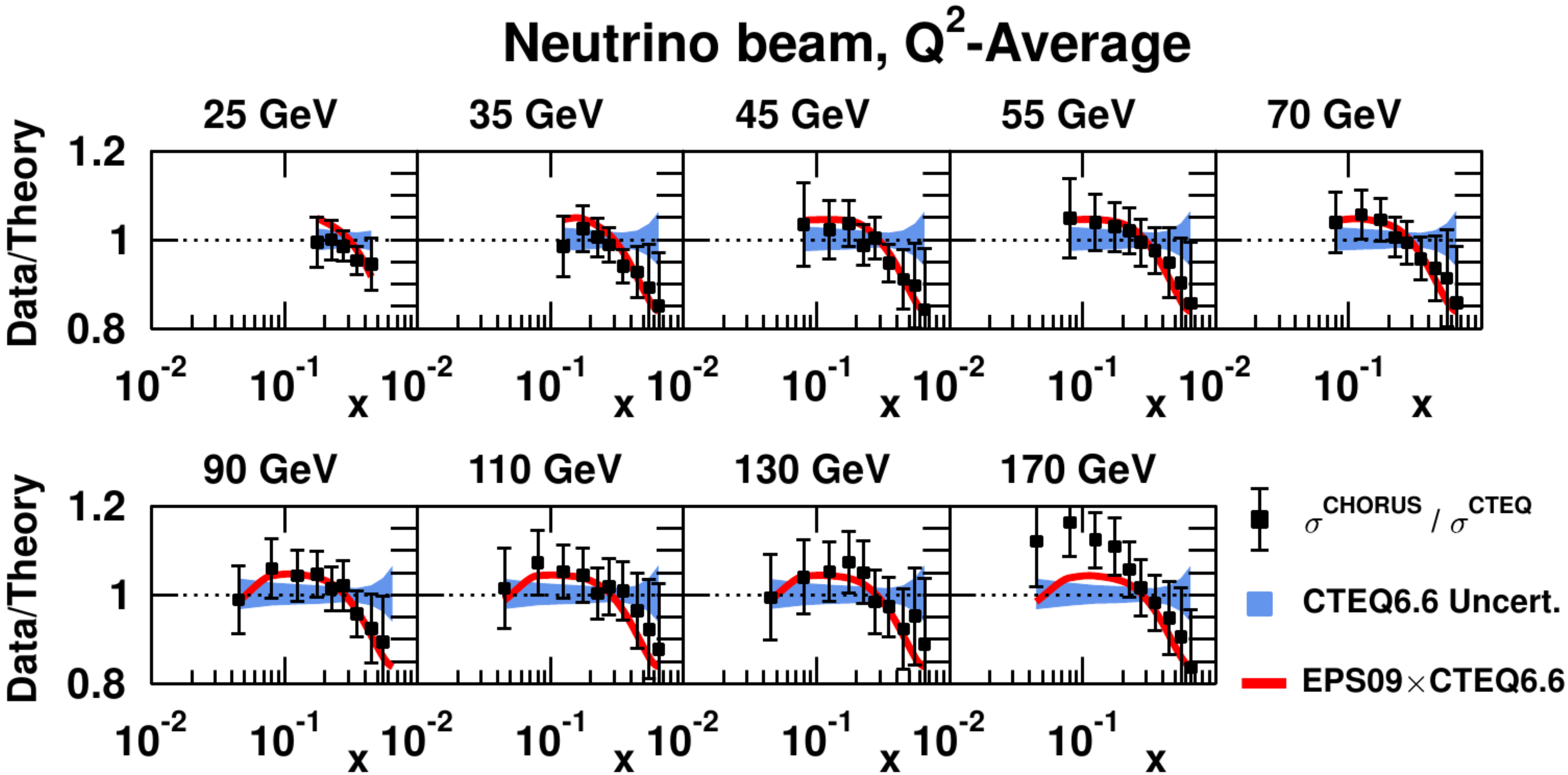
$$R^{\mathrm{CTEQ6.6}} \equiv \frac{\sigma^{\nu,\overline{\nu}}\,(\mathrm{Experimental})}{\sigma^{\nu,\overline{\nu}}\,(\mathrm{CTEQ6.6})}$$

← *virtually independent of Q^2*

Neutrinos: Paukkunen & Salgado

JHEP 1007 (2010) 032

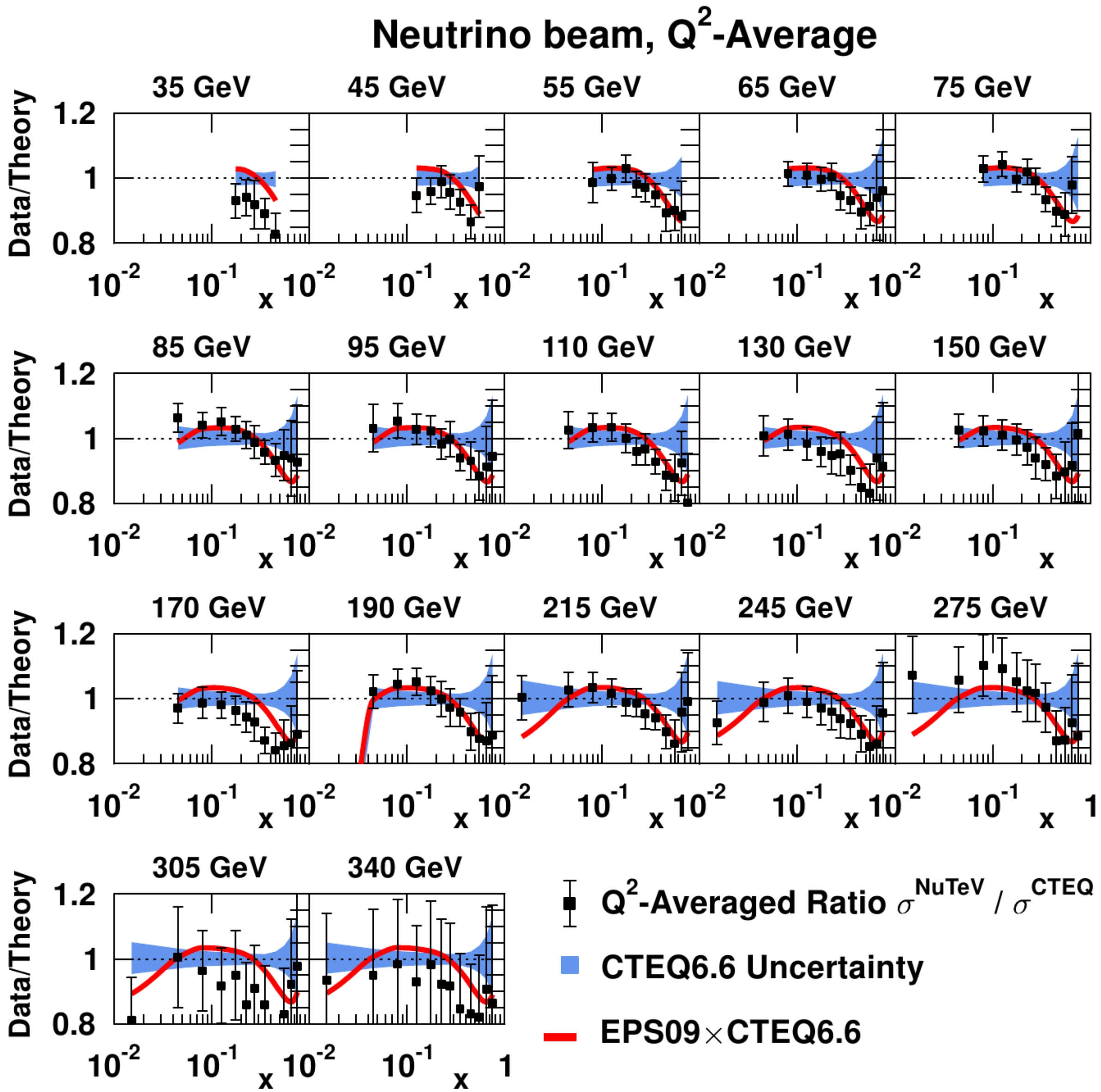
- For example, the CHORUS data in an excellent agreement with the EPS09 and CTEQ6.6



Neutrinos: Paukkunen & Salgado

JHEP 1007 (2010) 032

- Neutrino-energy-dependent inconsistencies in the NuTeV data



Neutrinos: Paukkunen & Salgado

Phys.Rev.Lett. 110 (2013) 212301

- Average also over the neutrino energy

- The NuTeV neutrino data systematically below the rest

→

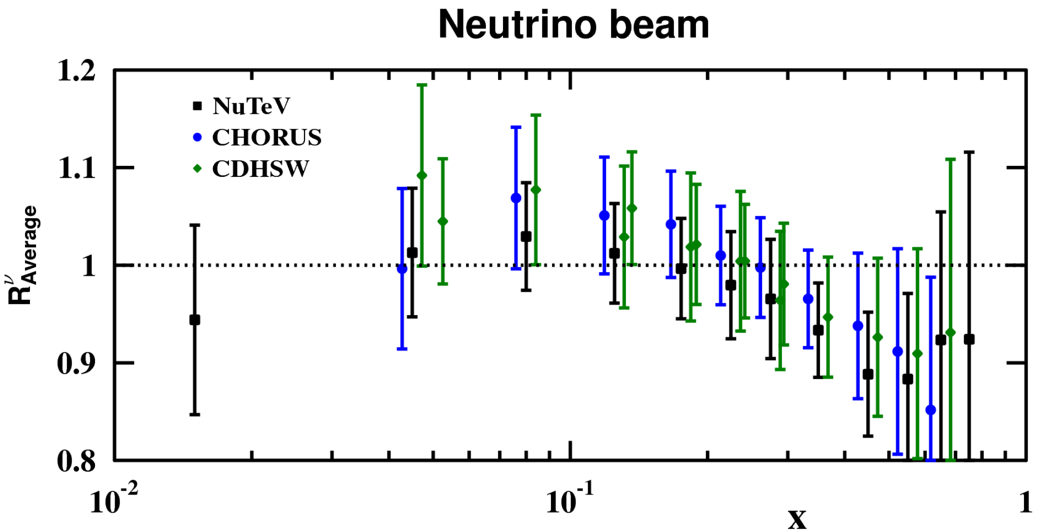
Tension in a global fit

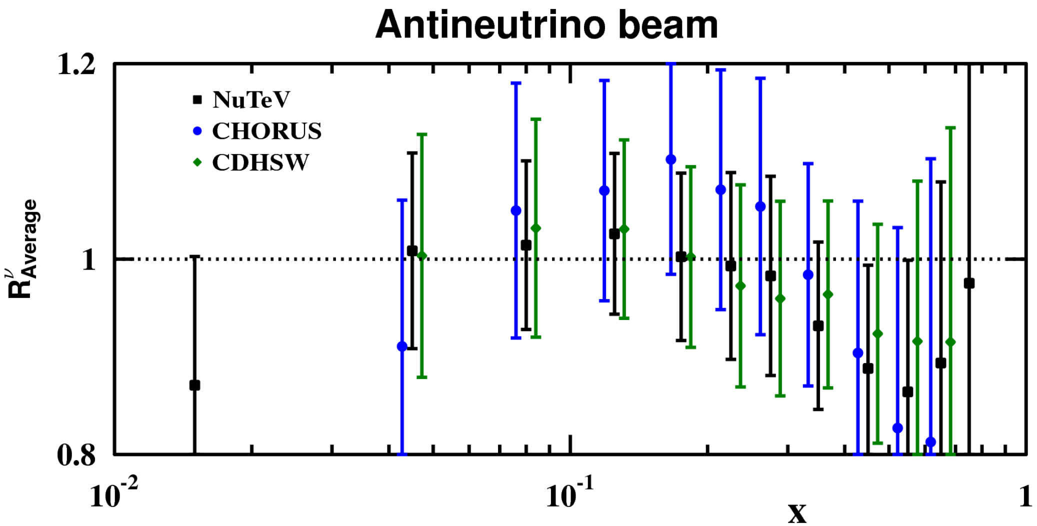
- However, the <u>shape</u> appears similar in all independent data sets.

- **A way out:** divide by the integrated cross-section for each beam energy

$$I^{\nu}_{\rm exp}(E) \equiv \sum_{i\in \text{fixed } E} \sigma_{{\rm exp},i}(x,y,E) \times B_i(x,y)$$

$$\overline{R}^{\nu}(x,y,E) \equiv \frac{\sigma^{\nu}_{\rm exp}(x,y,E)/I^{\nu}_{\rm exp}(E)}{\sigma^{\nu}_{\rm CTEQ6.6}(x,y,E)/I^{\nu}_{\rm CTEQ6.6}(E)}.$$





Neutrinos: Paukkunen & Salgado

Phys.Rev.Lett. 110 (2013) 212301

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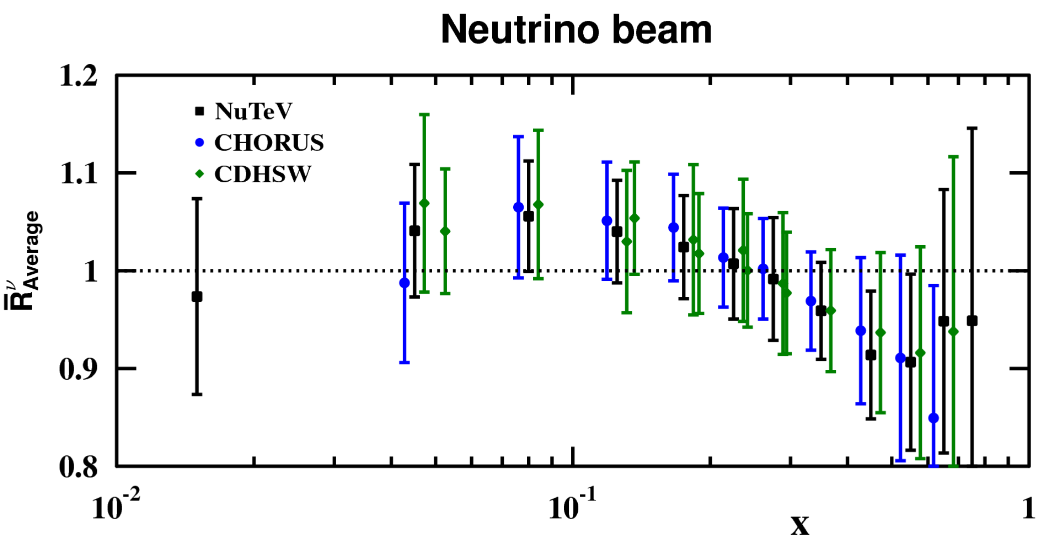
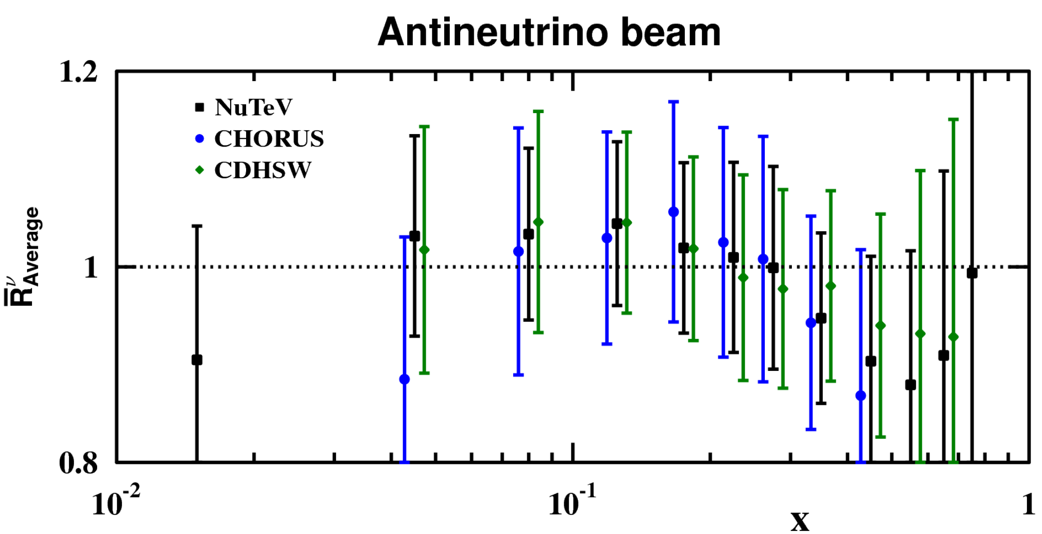




Neutrinos: Paukkunen & Salgado

Phys.Rev.Lett. 110 (2013) 212301

- An excellent agreement with e.g. CTEQ6.6+EPS09 nuclear PDFs

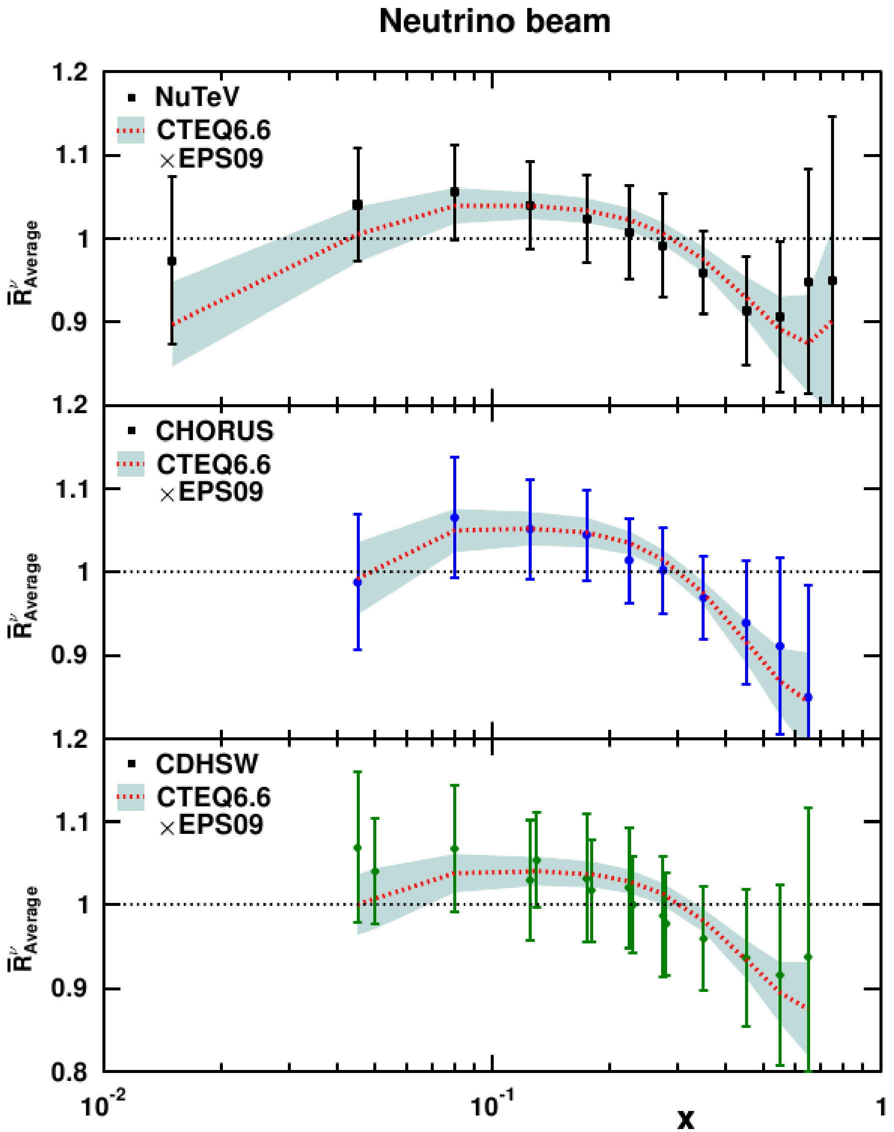
- A novel PDF re-weighting (not the NNPDF one) method was devised to reinforce the compatibilty

  With the normalization, OK

  Without the normalization the result of nCTEQ was “recovered” (for the NuTeV data).

- No reason to believe that the factorization would be violated.

- Points to an underestimation of the experimental errors (NuTeV)



Neutrinos: DSSZ

- **The DSSZ global fit included the neutrino data with no obvious difficulty:**

Included neutrino structure function data from NuTeV, CHORUS & CDHSW

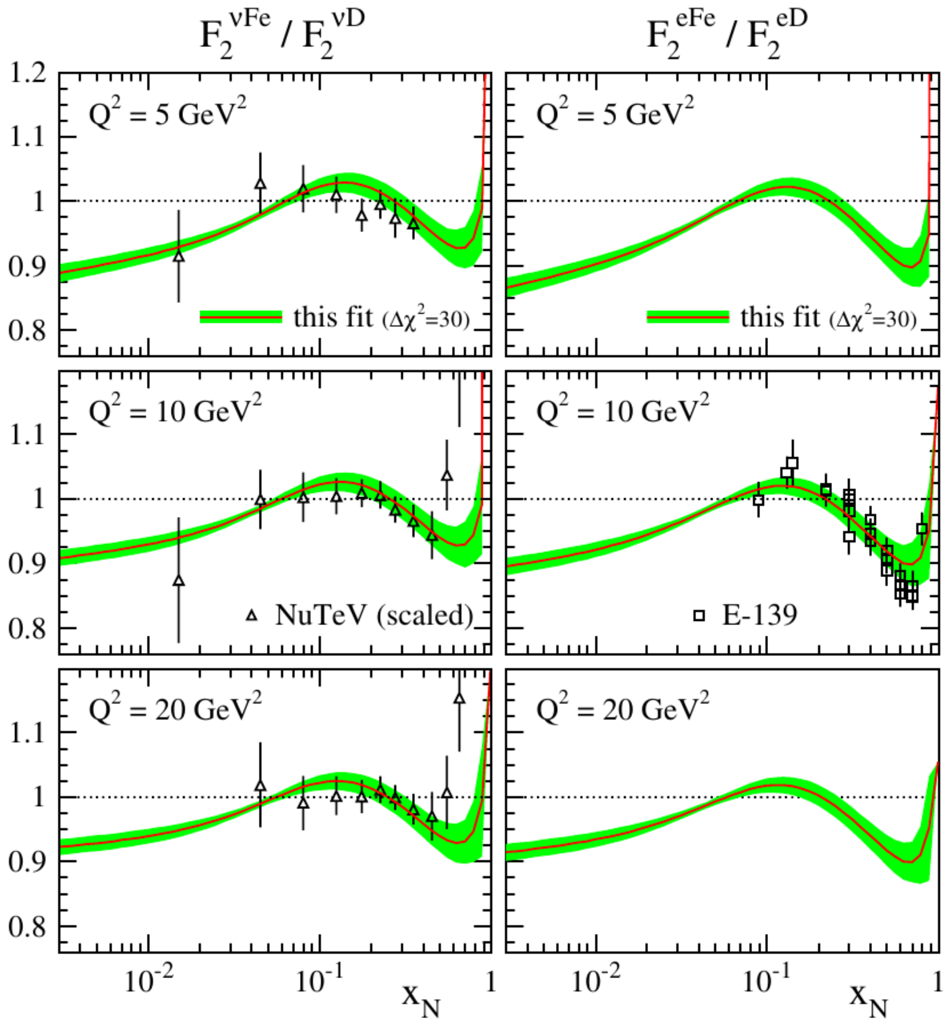
much more scarce than the absolute cross-section data

Used MSTW2008 free proton PDFs as a baseline

this set was already constrained by the NuTeV data

Added the MSTW2008 uncertainties in quadrature to the experimental errors

as if they were point-to-point uncorrelated errors.



- Given all this, the neutrino data did not carry as large weight as e.g. in the nCTEQ work

III Exciting dijet result from the LHC p+Pb run

The CMS dijets in p+Pb

- CMS has measured dijets using the 2013 p+Pb data
- Data binned in dijet "pseudorapidity"

$$\eta_{\text{dijet}} \equiv (\eta_1 + \eta_2)/2,$$

pseudorapidities of
the individual jets

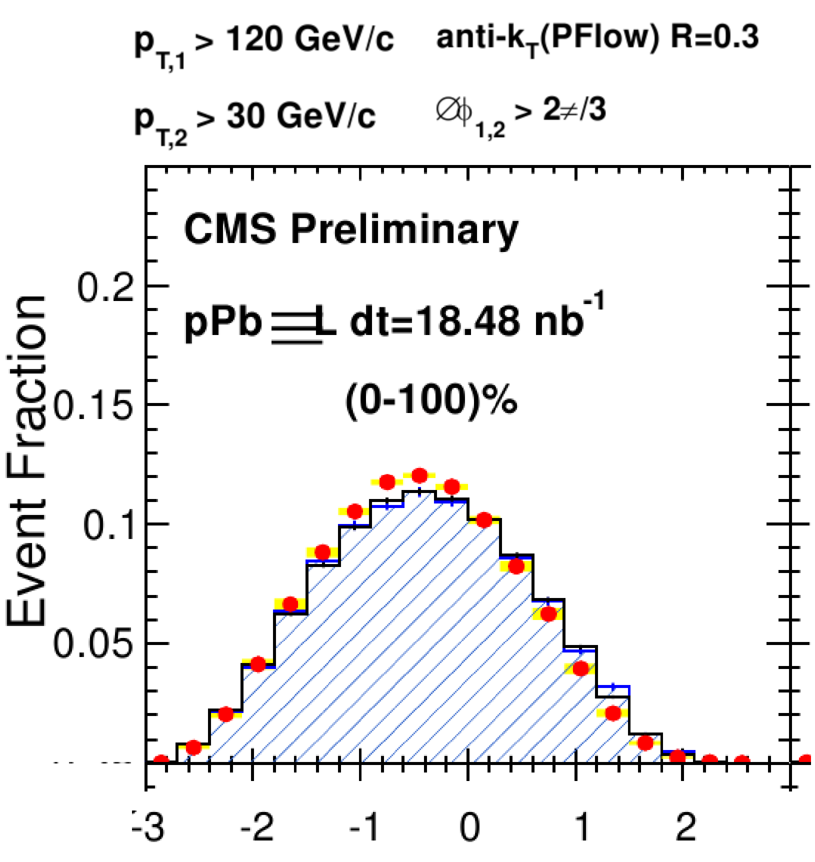
- Note the rapidity shift

$$\eta_{\text{shift}} \equiv 0.5 \log\left(E_{\text{Pb}}/E_{\text{p}}\right) \approx -0.465$$

Pb → ← p

(results presented in the collider frame)

CMS PAS HIN-13-001

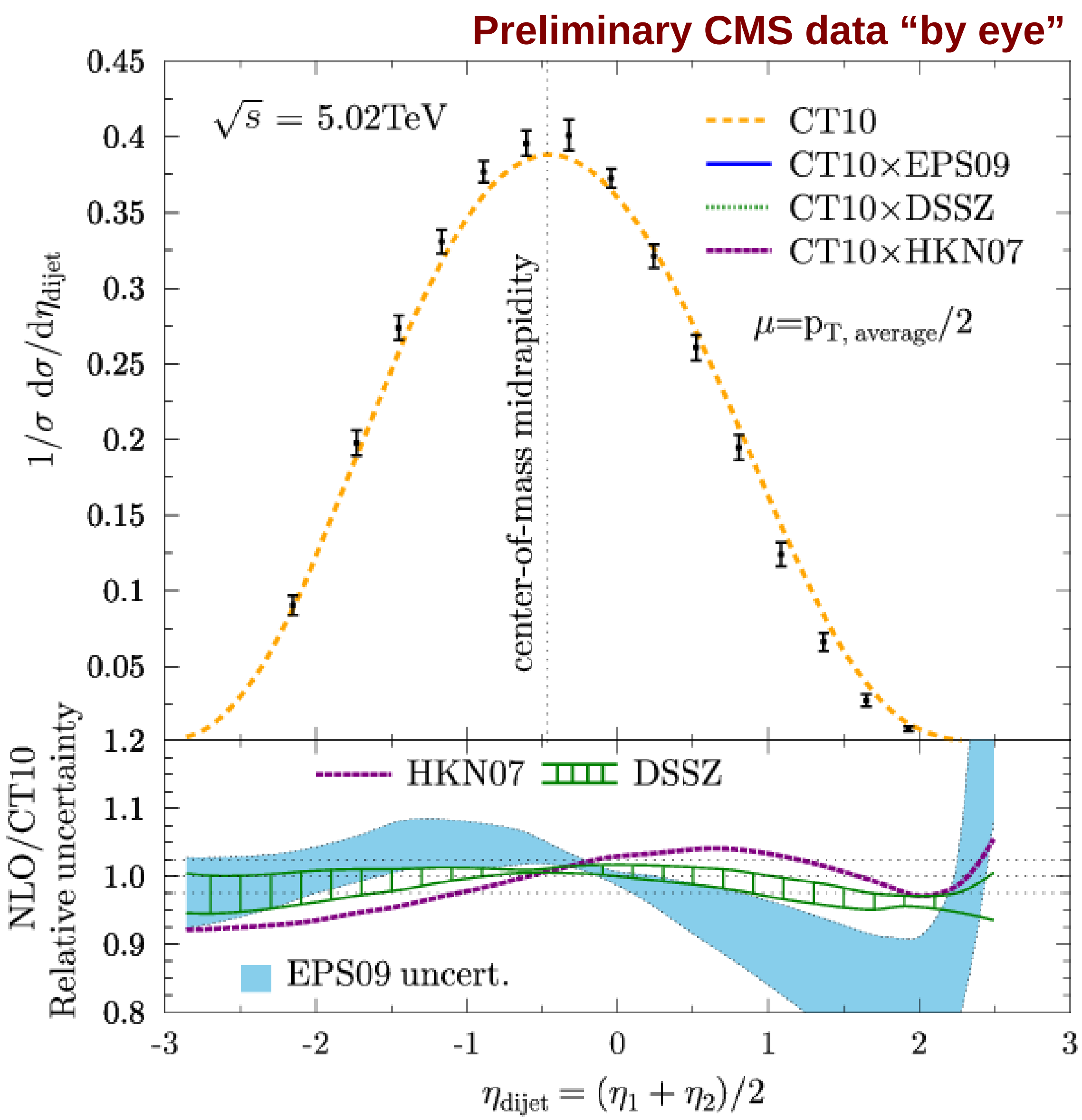


$$\eta_{\text{dijet}} \equiv (\eta_1 + \eta_2)/2,$$

- Is this sensitive to the nuclear (gluon) PDF modifications?

The CMS dijets in p+Pb

Eskola, Paukkunen, Salgado, arXiv:1308.6733



The CMS dijets in p+Pb

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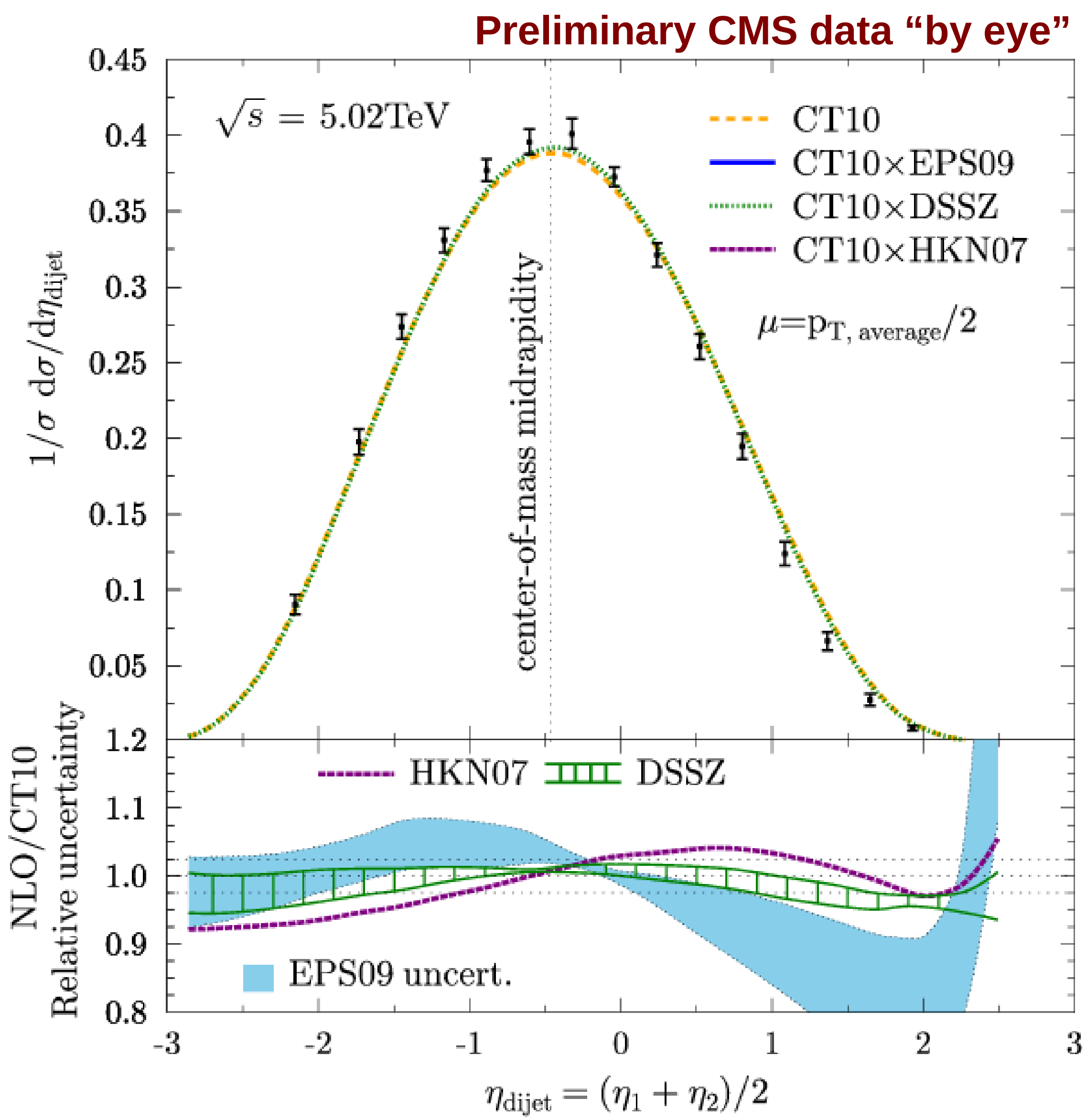

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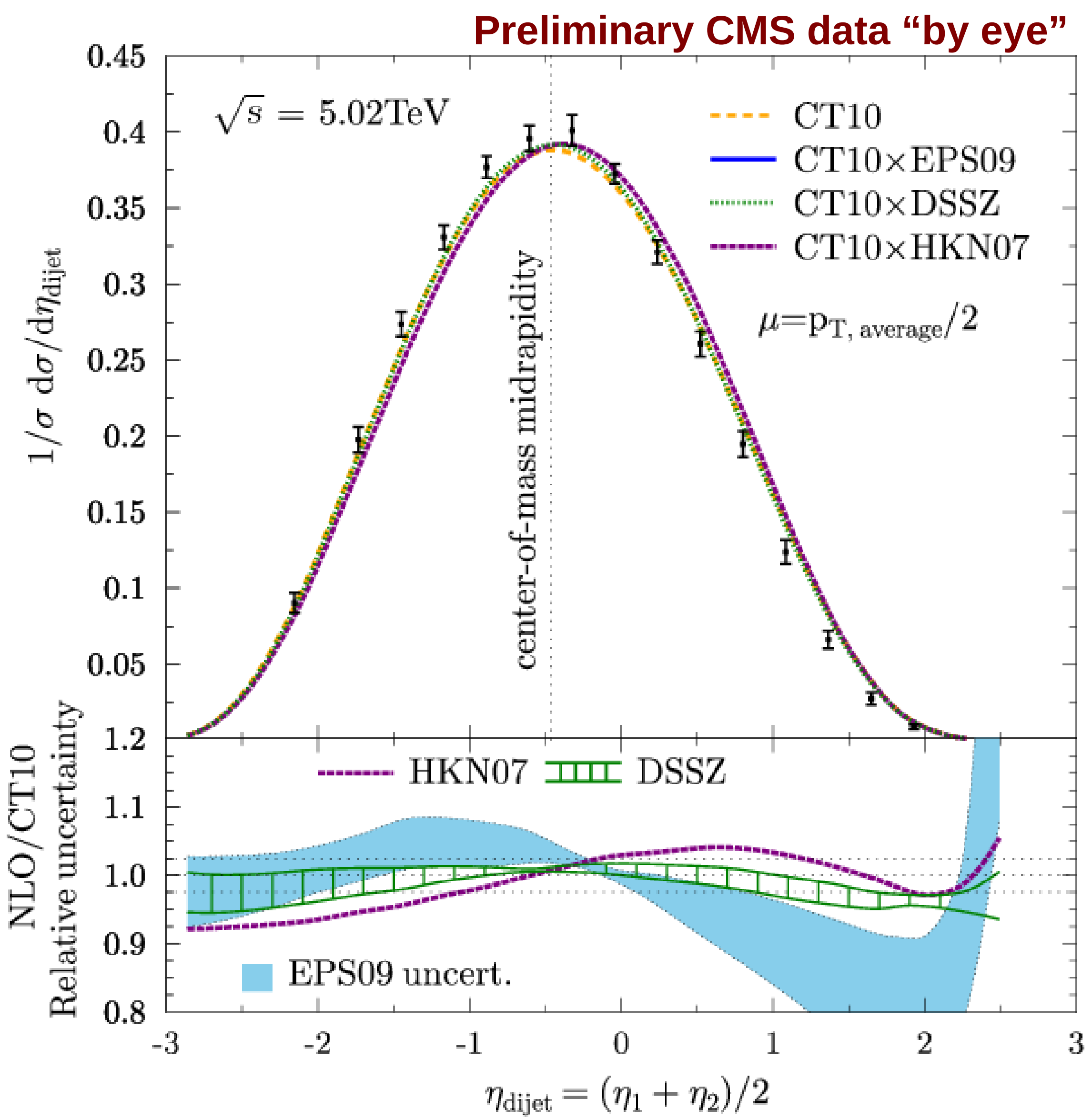

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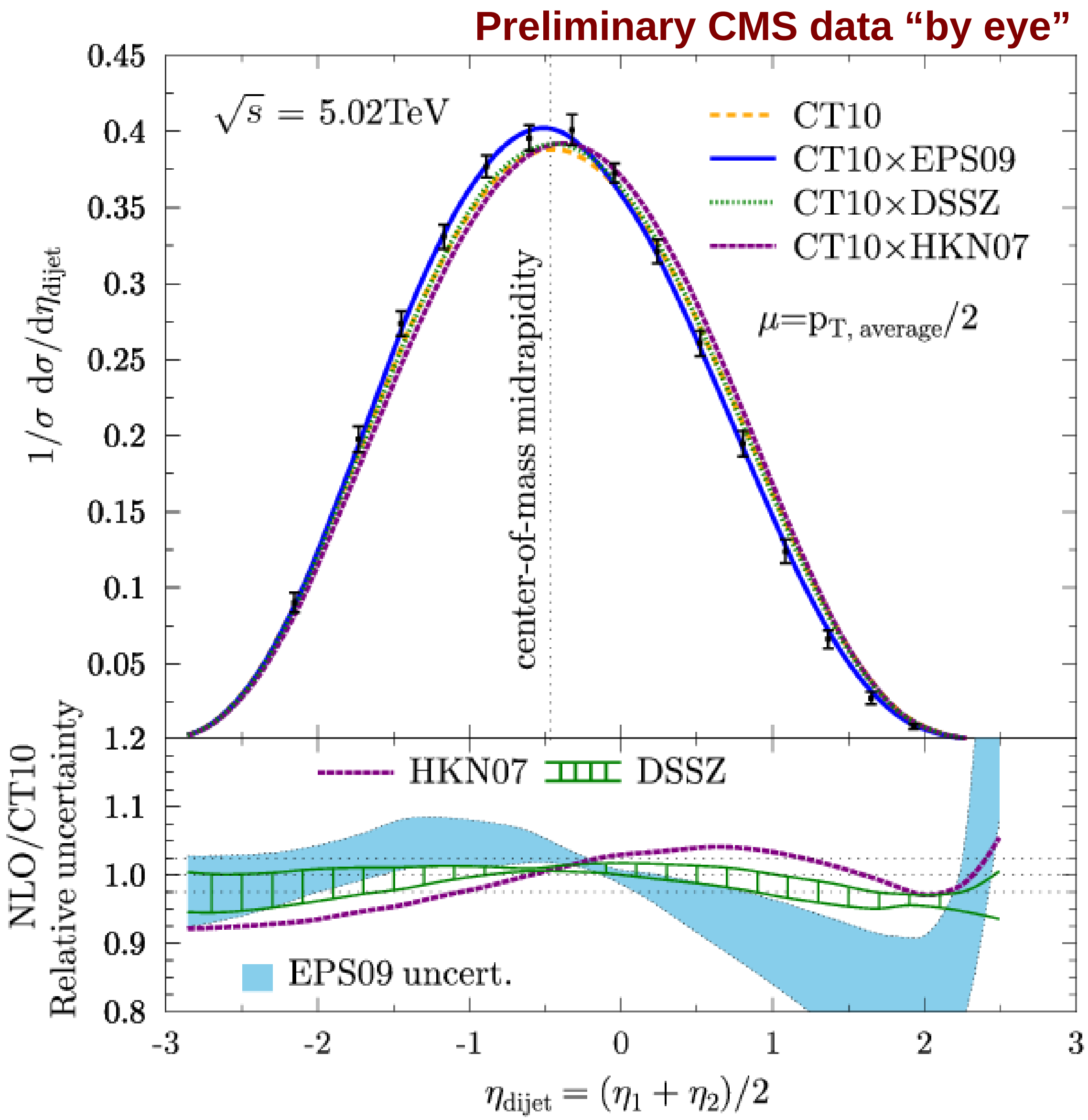


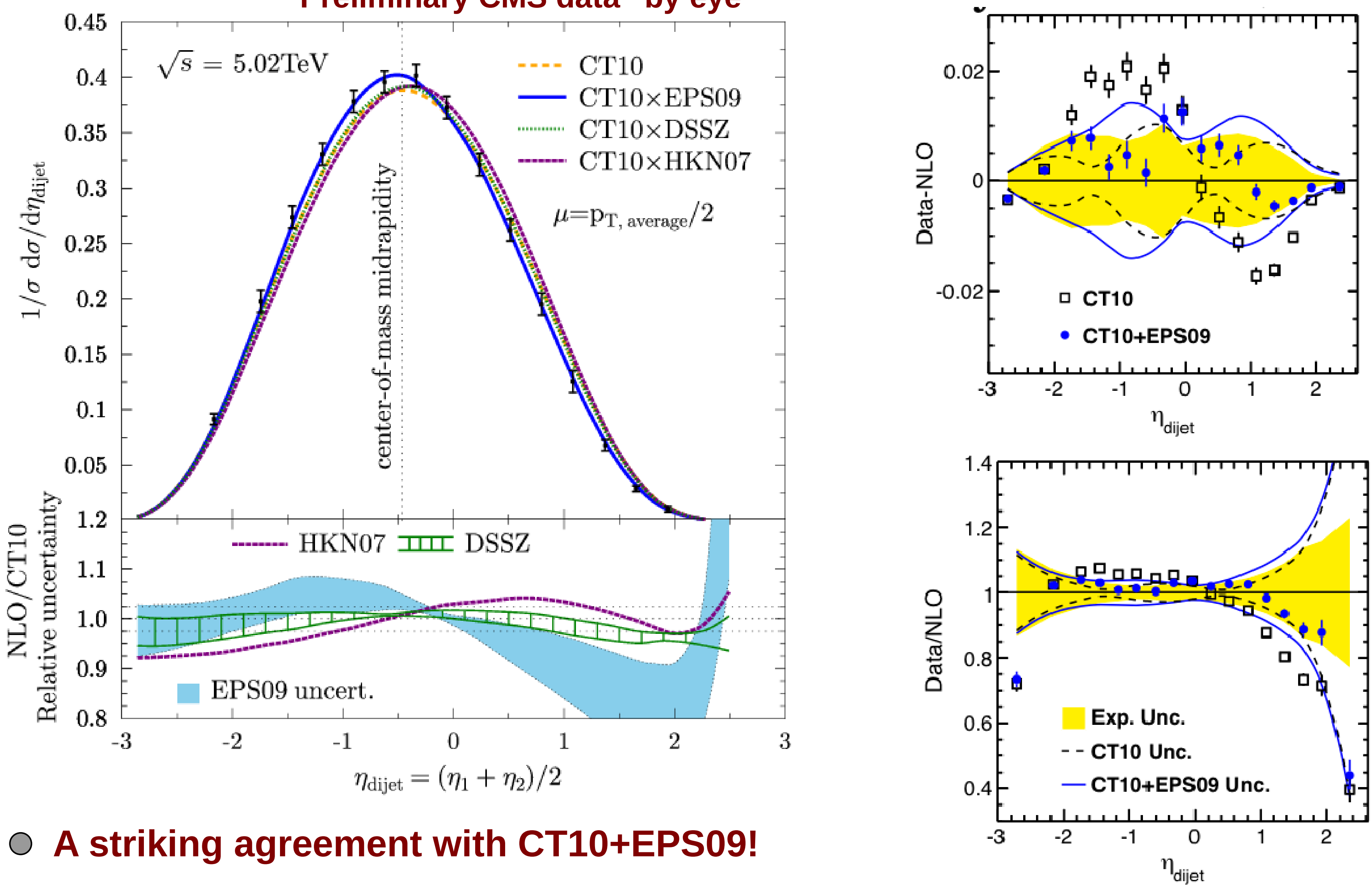
The CMS dijets in p+Pb

Eskola, Paukkunen, Salgado, arXiv:1308.6733

- **Comparison to the NLO calculations – the gluon PDFs make a difference!**

Preliminary CMS data "by eye"

Doga Gulhan, IS2013, Spain



- **A striking agreement with CT10+EPS09!**

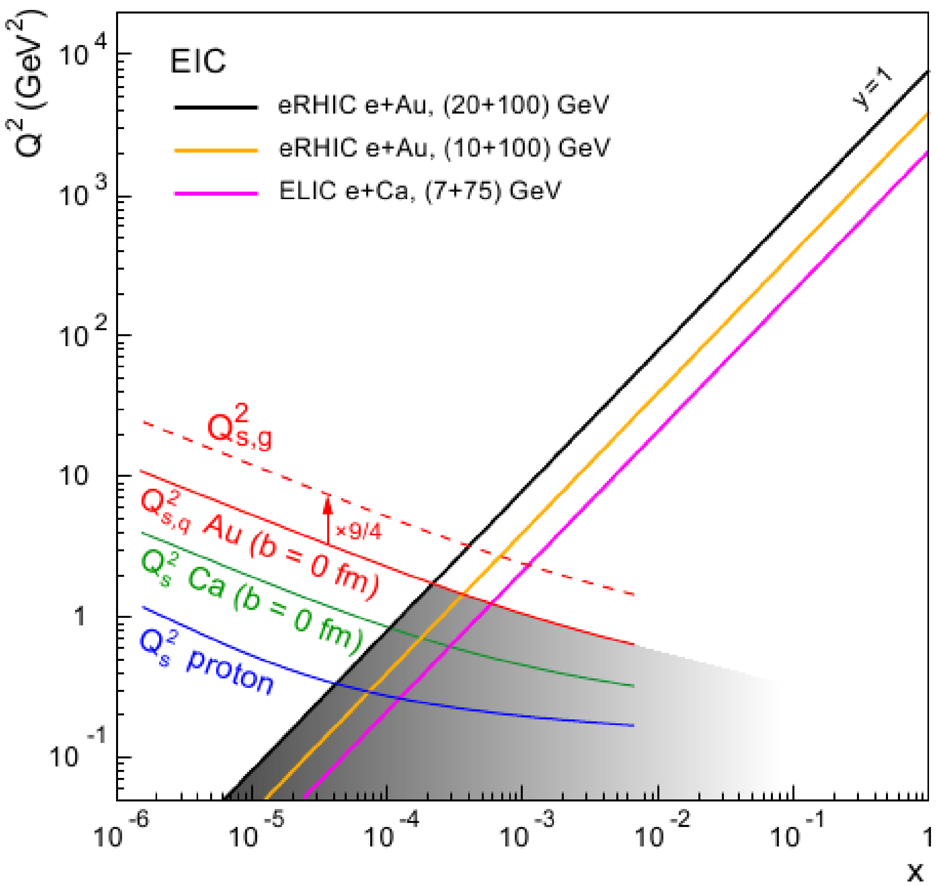
IV LHeC / EIC prospects

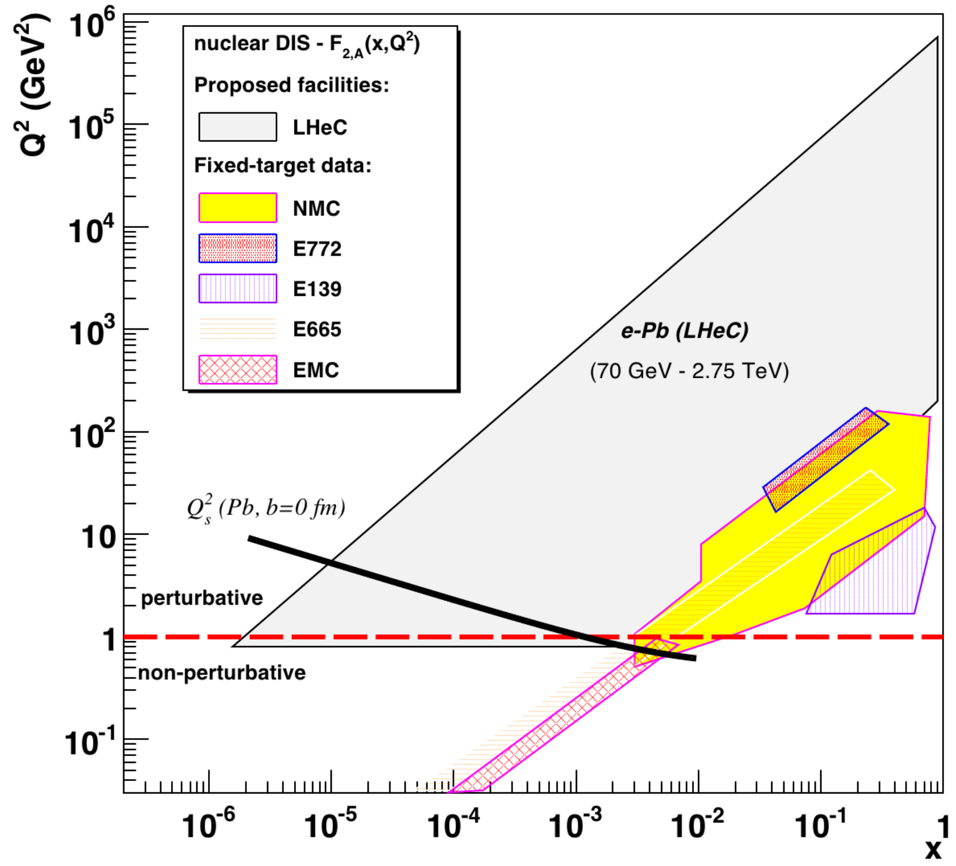
LHeC: arXiv:1306.2486, arXiv:1206.2913

EIC: Work with the BNL EIC team

Kinematics: EIC vs. LHeC

- Both colliders would enlarge the kinematic coverage of the present nuclear DIS data - LHeC hugely, EIC a bit less





- Estimate the impact of the LHeC and EIC data on the nPDFs by a direct fit to a sample of pseudodata

The LHeC & EIC pseudodata

- Samples of NC pseudodata (by N. Armesto for LHeC & M. Lamont for EIC) for reduced cross-sections

$$\sigma_r^{NC} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{NC}}{dx dQ^2} = F_2 \left[1 - \frac{y^2}{Y_+} \frac{F_L}{F_2}\right] \qquad Y_+ = 1 + (1-y)^2$$

was generated from using assuming:

- E_{lepton} = 50 GeV, E_p = 7000 GeV, E_{Pb} = 2750 GeV , E_{Ca} = 3500 GeV — **LHeC**

in the kinematical window: $10^{-5} < x < 0.01$ & $Q^2 < 1000$ GeV^2

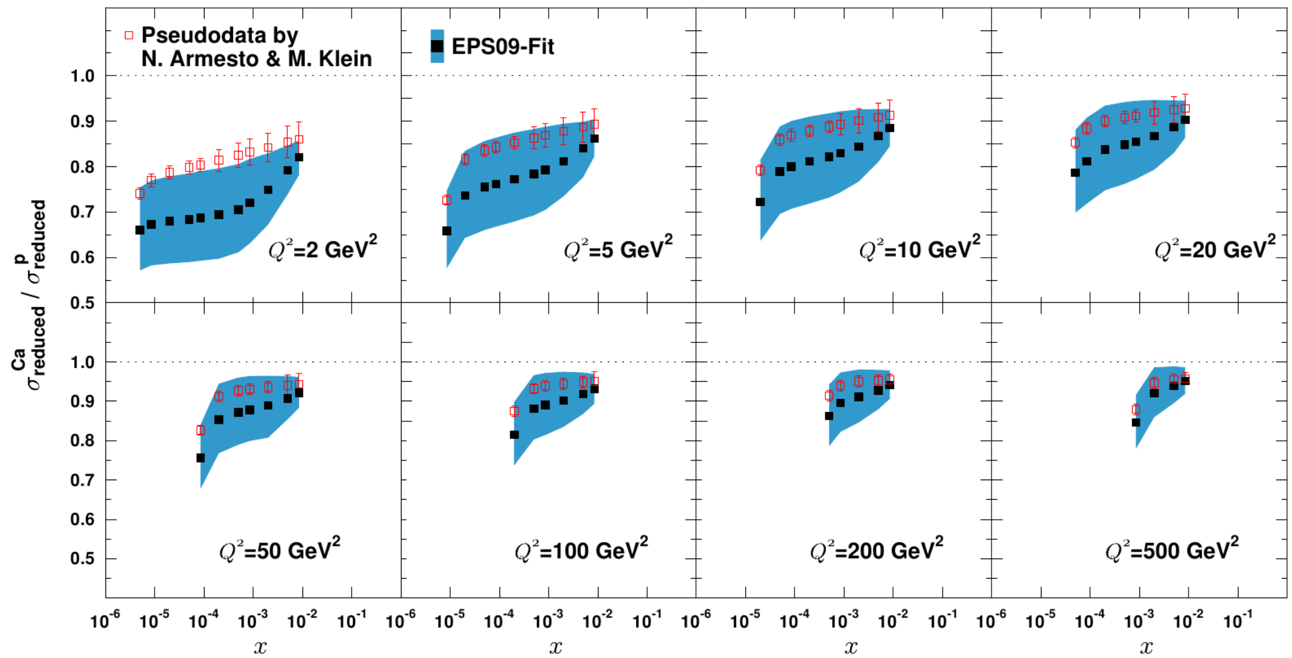
- E_{lepton} = 5 GeV, $E_{p,Au,Cu}$ = 50, 75, 100 GeV (Phase 1)
  E_{lepton} = 20 GeV, $E_{p,Au,Cu}$ = 50, 75, 100 GeV (Phase 2) — **EIC**

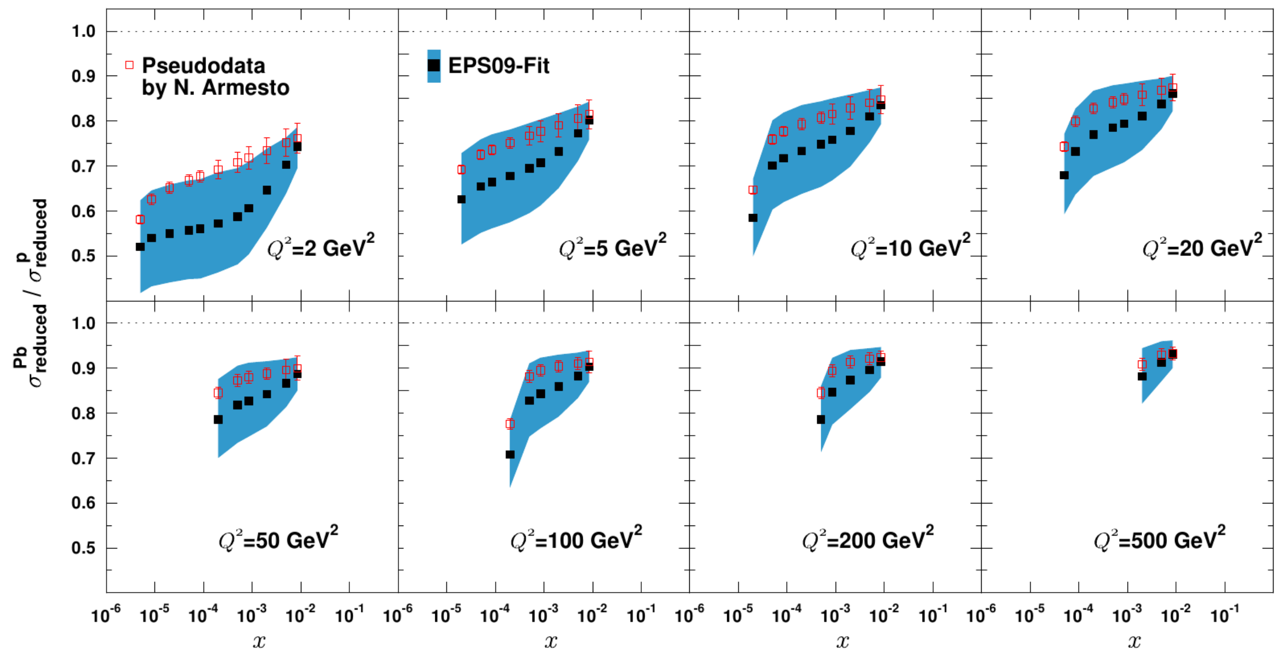
in the kinematical window: $10^{-3} < x < 1$ & $Q^2 < 500$ GeV^2

- Nuclear effects according to a dipole model (Eur. Phys. J. C26 (2002) 35-43) for LHeC and from EPS09LO for EIC.
- The inclusive cross-sections were combined to ratios

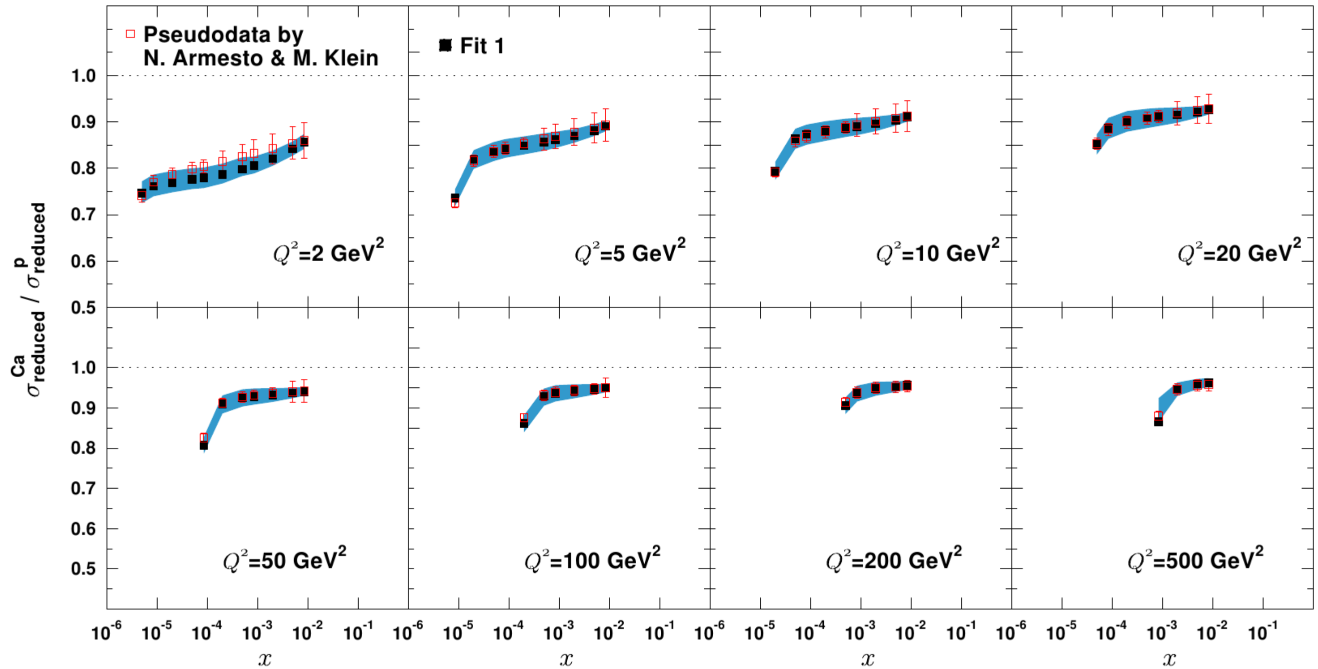
$$\frac{\sigma^{\rm Ca}_{\rm reduced}(x,Q^2)}{\sigma^{\rm p}_{\rm reduced}(x,Q^2)}, \quad \text{and} \quad \frac{\sigma^{\rm Pb}_{\rm reduced}(x,Q^2)}{\sigma^{\rm p}_{\rm reduced}(x,Q^2)}$$

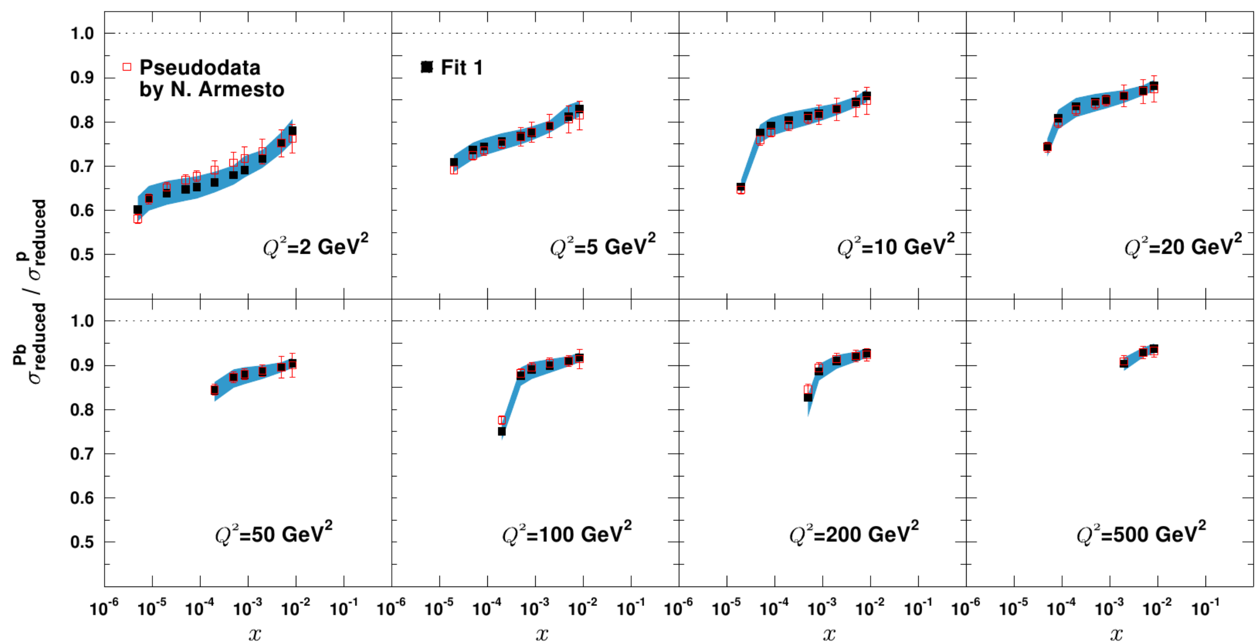
Before the fit: the LheC pseudodata vs. EPS09



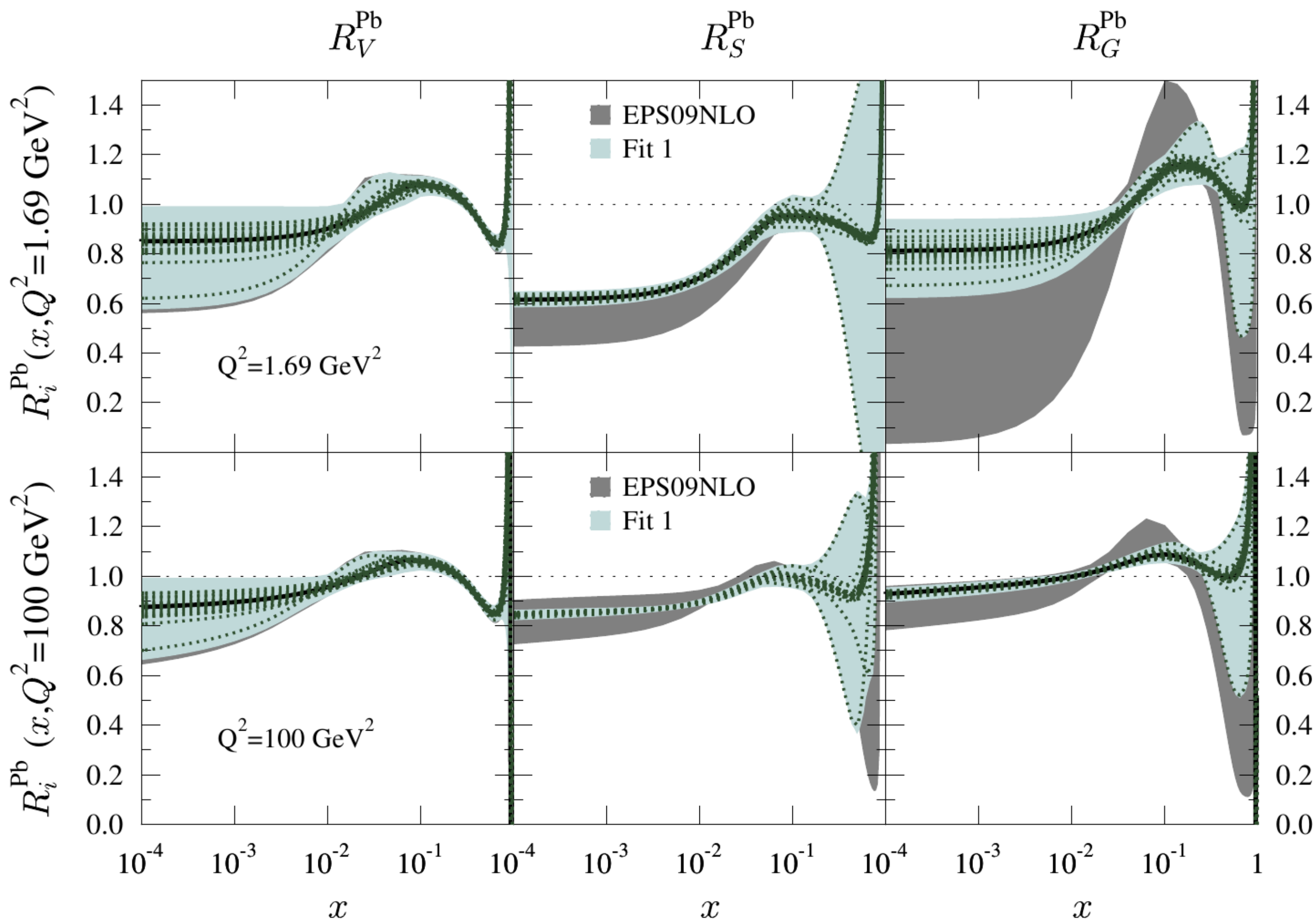


After the fit: LHeC



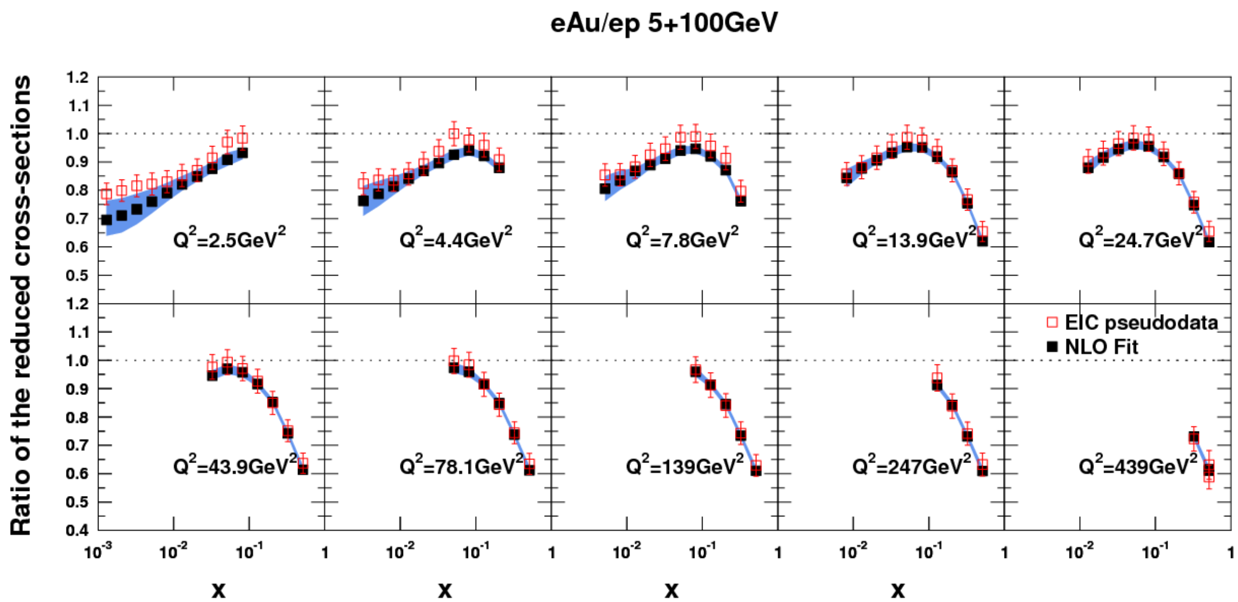


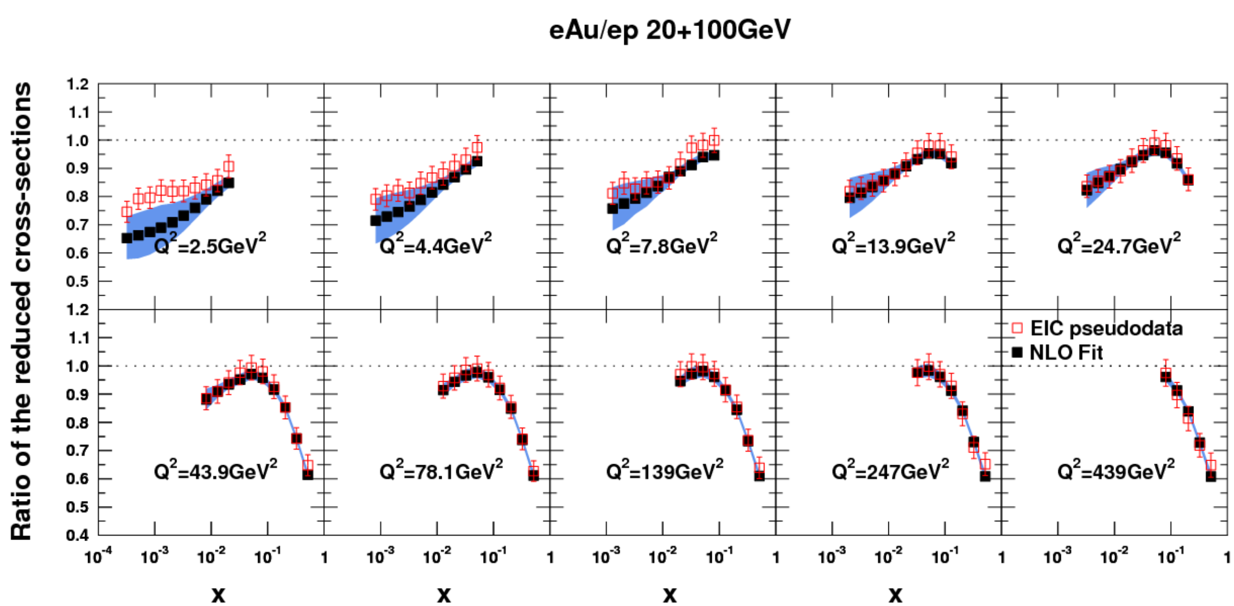
Effect in the nuclear modificaton factors, LHeC



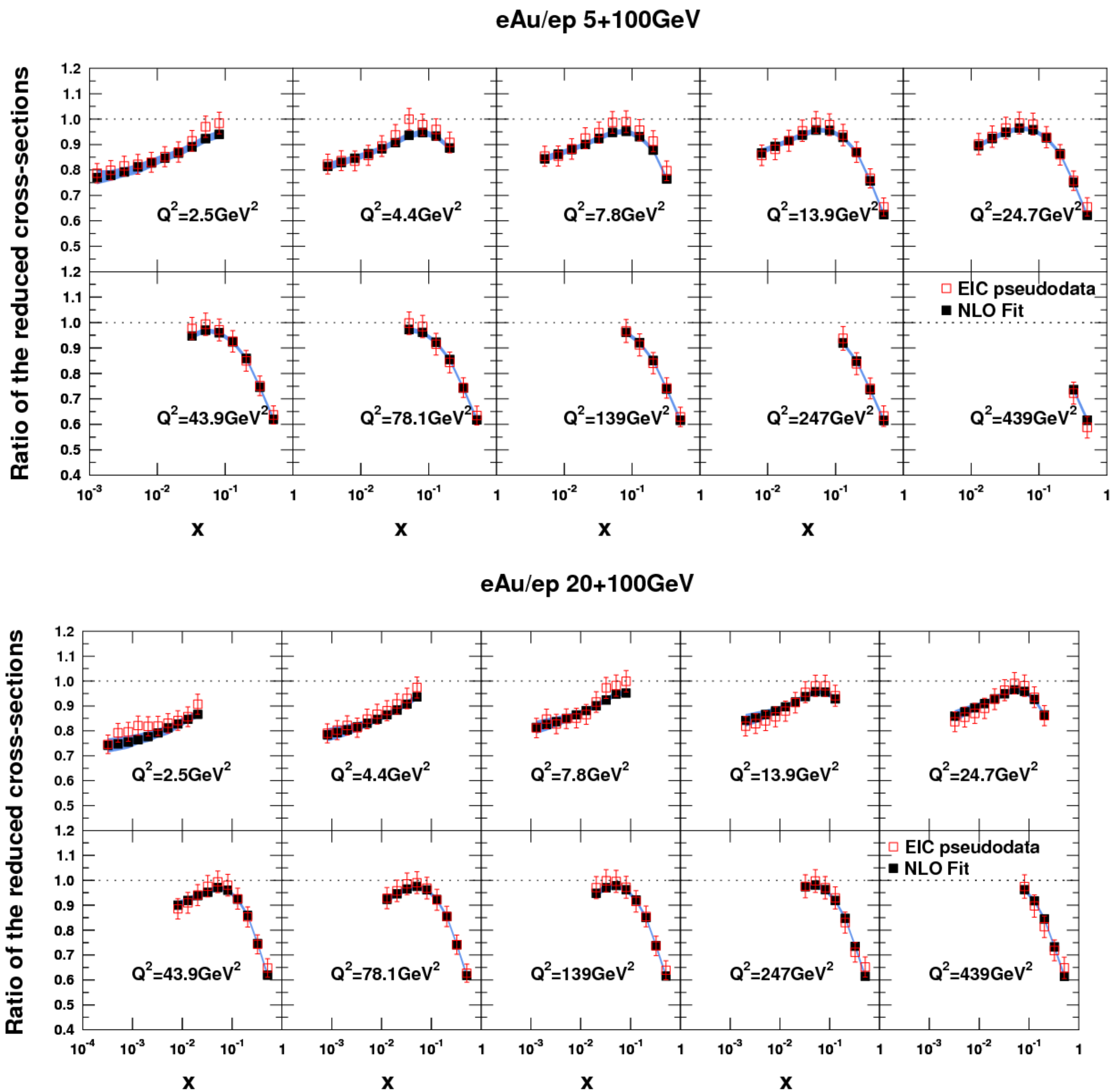
- **A drastic reduction in the small-x gluon and sea quark uncertainties**

Before the fit: some EIC pseudodata vs. baseline fit



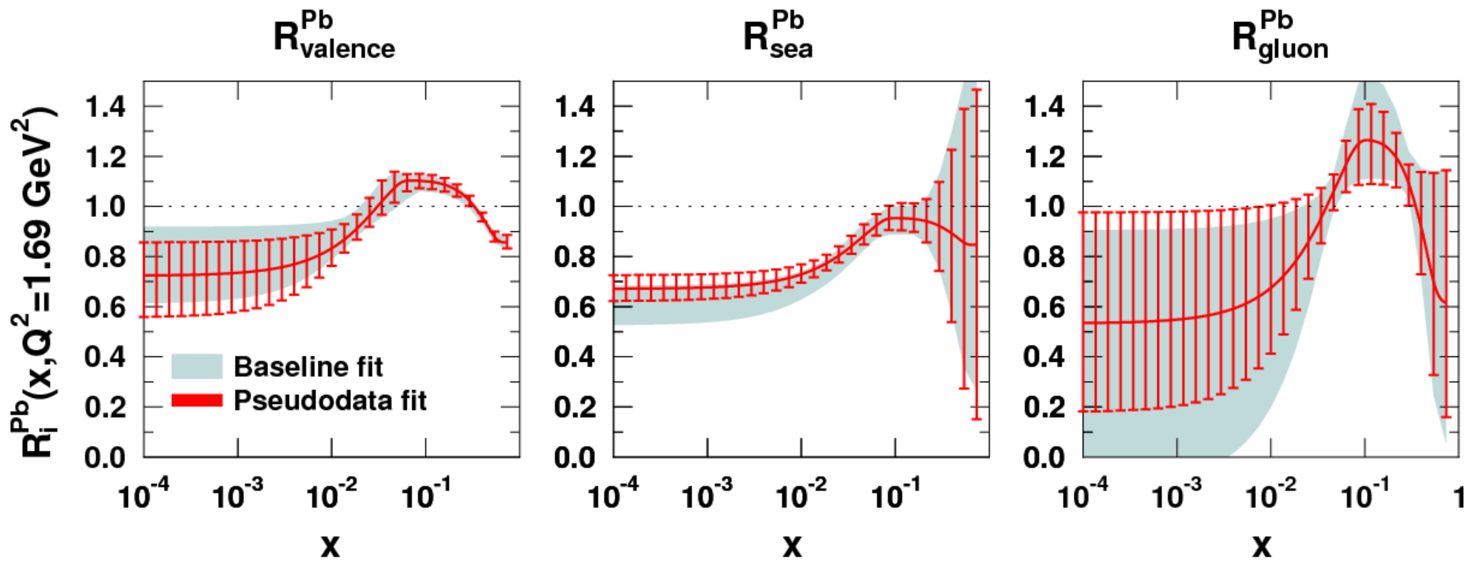


After the fit: some EIC pseudodata vs. new fit

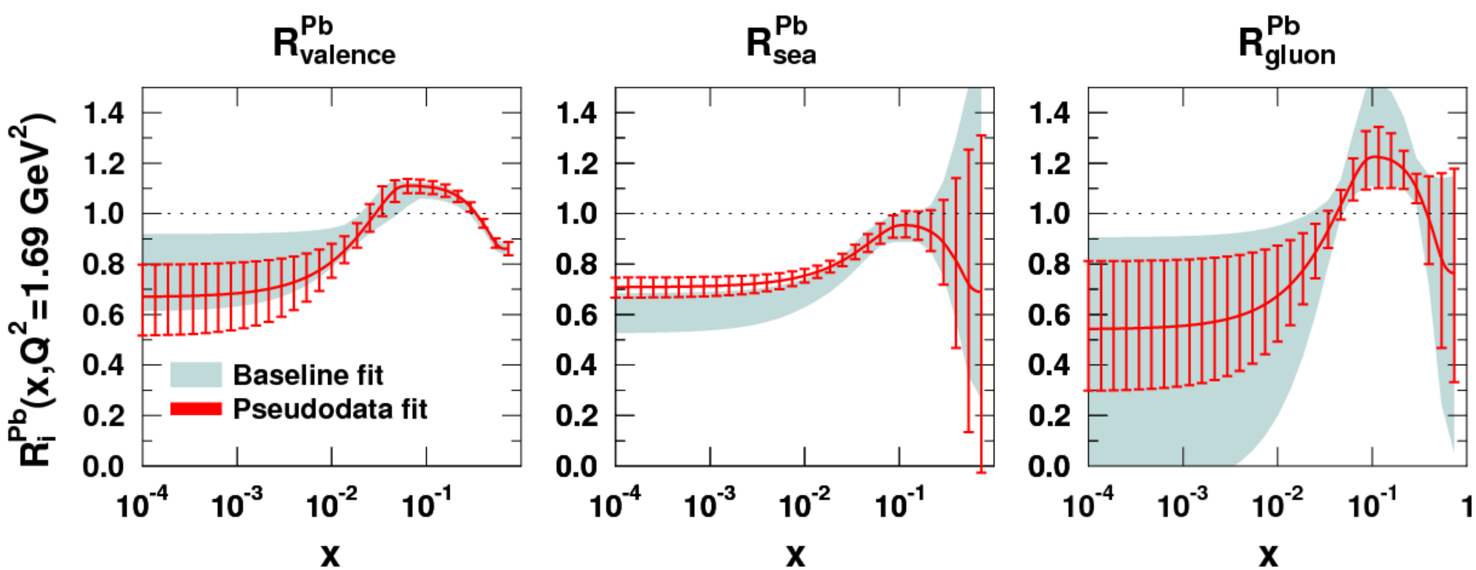


Effects in the nuclear modificaton factors: EIC

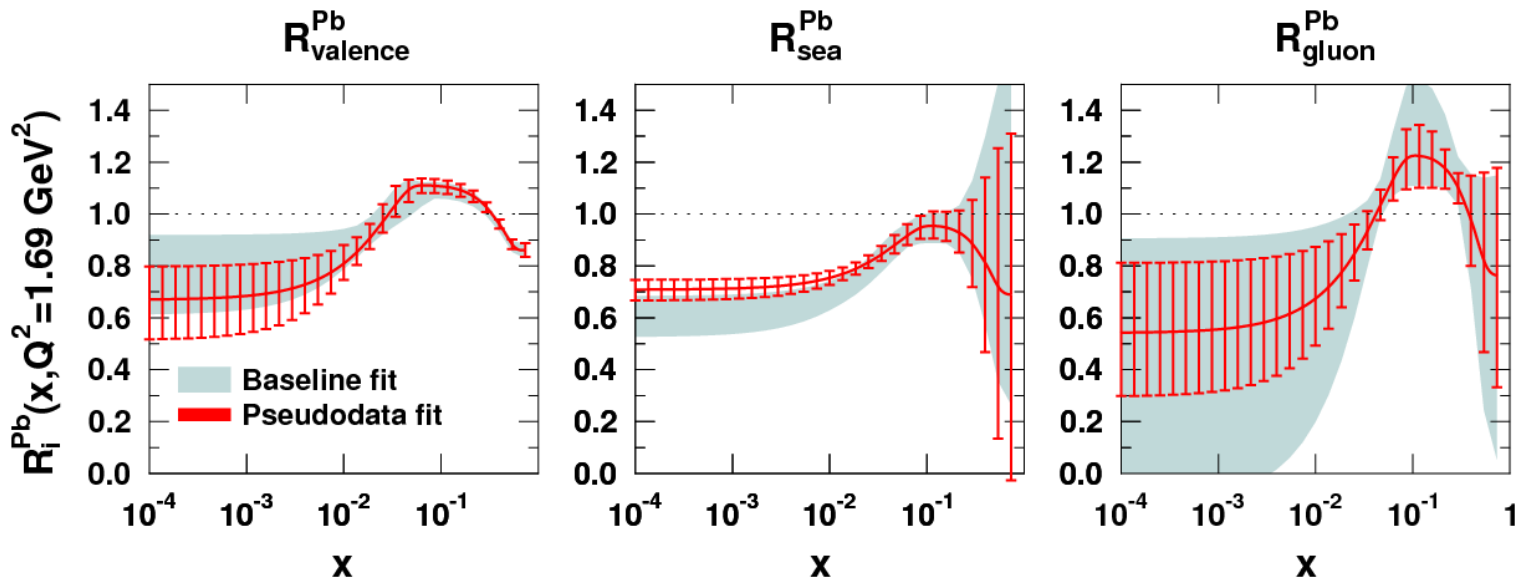
“Phase 1“

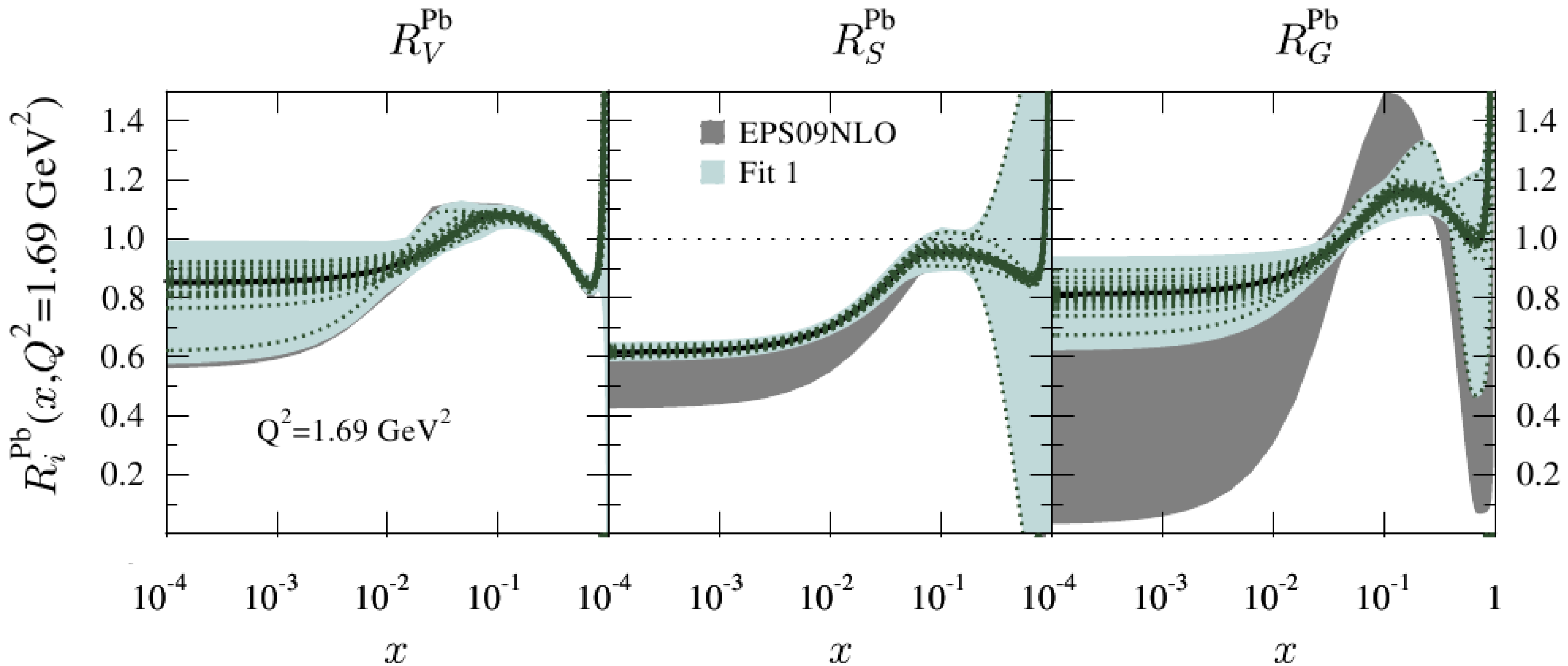


“Phase 2“



Effects in the nuclear modificaton factors: LHeC vs. EIC





- **LHeC would reach smaller values of x --> better constraints**

Summary

- **Presented the current status of the nPDFs**

  Large differences among independent fits.
  The LHC p+Pb data are expected to have an impact

- **Discussed the issue of neutrino-nucleus DIS**

  The recent controversy could be explained by inaccuracies in the experimental absolute normalization

- **Flashed the first dijet measurements from the LHC p+Pb runs**

  Already this first data could discriminate between different sets of nPDFs. Much more to come (W, Z, direct photon, ...)

- **Discussed LHeC & EIC prospects**

  Would allow to study the nPDFs (at small x) to a similar precision as done in HERA for the free proton